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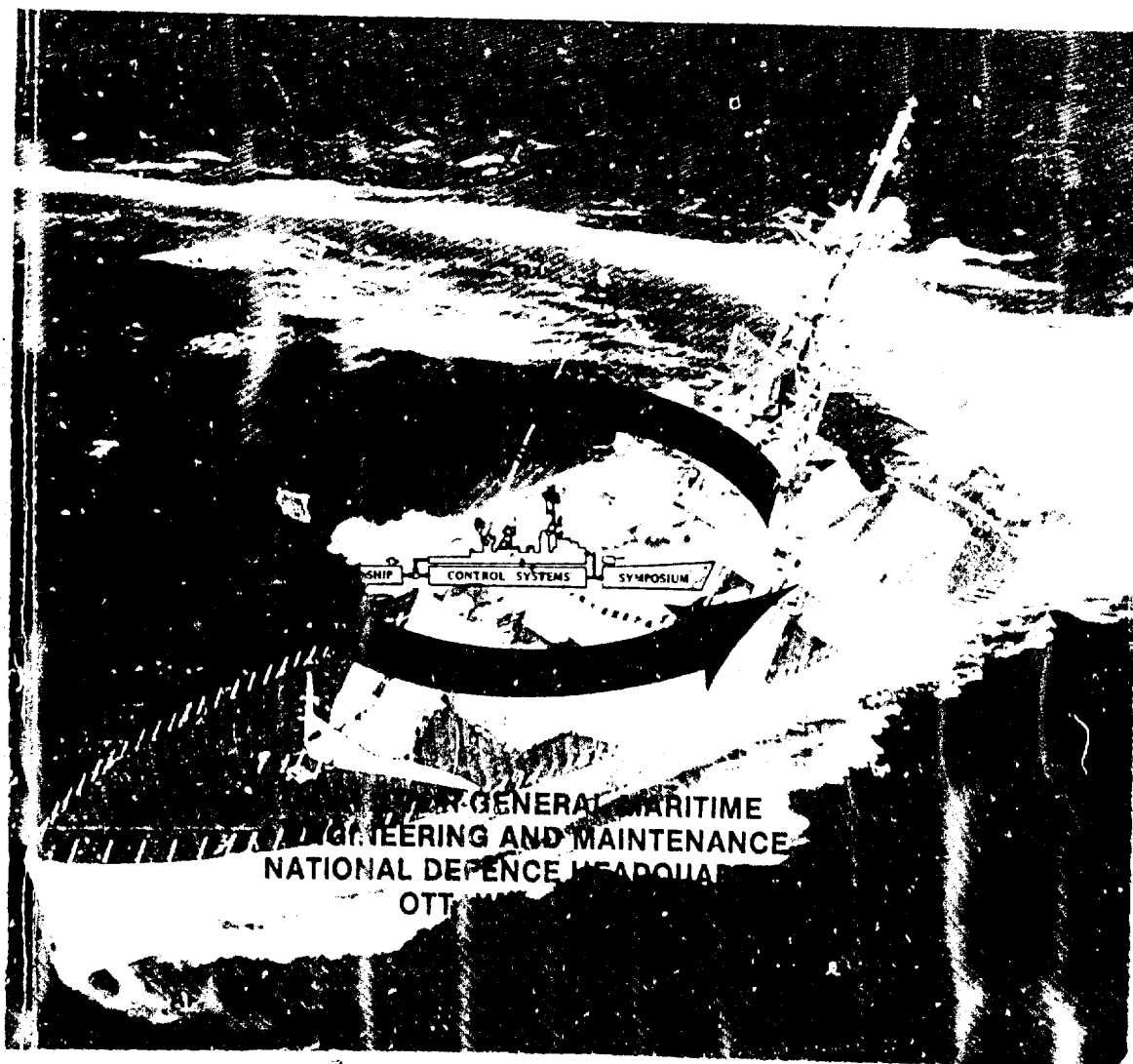
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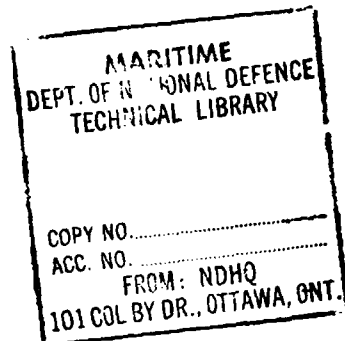
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VOLUME 5



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FOREWORD

The Director General Maritime Engineering and Maintenance (DGMEM) is pleased to present the Proceedings of the Sixth Ship Control System Symposium held at the Chateau Laurier/National Conference Centre complex in Ottawa, Canada, 26-30 October 1981. This is the sixth in a series of symposia on ship control systems. The First Ship Control Systems Symposium was convened in 1966.

The technical papers presented at the Symposium and published in these proceedings cover the entire spectrum of ship control systems and provide an insight into technological developments which are continuously offering the ship control system designer new options in addressing the complex man/machine operation. The microprocessor and its apparently unlimited development potential in future digital, distributed control systems appears ready to reshape the conventional concepts now so familiar in control system designs. There are many concerns that the advantages of the new technologies will be negated by the inability of training systems to graduate technicians who can adequately cope with these new systems.

The response to "Call For Papers" was outstanding and the papers selection committee constrained by the time available for presentations, was hard pressed to make their final selections from the many fine abstracts submitted. The final papers represent a unique international flavour which includes authors from every facet of the ship control system community. The final program is a balance of both theoretical and practical control system papers.

These Proceedings constitute the major record of the Sixth Ship Control Systems Symposium. The contents indicate the success of the Symposium and provide some insight into the effort that was required to ensure this success. The Symposium organizing committee, advisory groups, publications branch, authors, session chairmen, international coordinators, clerical and administrative personnel, and management all provided positive and cooperative support to the many tasks that had to be performed in organizing and presenting the Symposium.

This Symposium has continued to explore and present a number of specific aspects of ship control systems and undoubtedly the next symposium will include new concepts and ideas which were unavailable for this Symposium. As in the past, we hope these Proceedings become a source document on ship control along with the previous proceedings. It is our hope that the Symposium has provided stimulation to those who will continue to advance this technical field.

Bruce H. Baxter
General Chairman

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Philip V. Penny
Technical Chairman

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COLLISION AVOIDANCE AND NAVIGATION FOR HIGH SPEED SHIPS
A REPORT ON HICANS

by CDR William Erickson, U.S. Navy
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Sperry Systems Management

ABSTRACT

While the need for automation of the bridge related function of collision avoidance and navigation is not yet universally accepted for conventional surface ships, such need for high speed ships is now appreciated. However, in the design and construction of the first NATO Hydrofoil (PHM-1), both collision avoidance and coastal navigation and piloting were left to be accomplished in the conventional (manual) way. The U.S. Navy now has installed a system aboard USS PEGASUS (PHM-1) which greatly improves the efficiency and safety of the PHM in these areas. This paper describes this system, the High Speed Ship Collision Avoidance and Navigation System (HICANS), both functionally and physically. In particular, the use of digital charts and TV projection of standard paper charts is described. The paper also describes the results to date of at-sea testing of the system aboard USS PEGASUS. When approved for service use, HICANS is scheduled to be installed in the five additional PHM's being built and will be a significant enhancement for other high speed ships.

INTRODUCTION

The USS PEGASUS (PHM-1) which was launched fully combat outfitted in November 1974 is described in reference (1) and is shown in Figure 1. An intensive test program, involving the combat system as well as the vessel, was followed by a deployment off the West Coast of the United States. A one-month independent operational evaluation (OPEVAL) was conducted by Commander, Operational Test and Evaluation Force (COMOPTEVFOR) in May 1976. The operational evaluation identified a need for improving the piloting and collision avoidance capabilities of the craft. As a result, an interim system, TANCAV, which was originally developed, installed, and evaluated aboard the Highpoint (PCH-1) by the Hydrofoil Special Trials Units (HYSTU) at Bremerton, Washington, was installed aboard the USS PEGASUS. This system, which was manually operated, used commercially available equipment to provide a TV picture of the nautical chart which was superimposed on a scan converted radar picture. By matching the radar video to the chart, this system enabled the own ship position to be shown relative to the charted land contours, buoys, channels, and hazards. This system was used as the primary navigation reference when flying at high speeds in pilotage waters.

In the spring of 1977, the Navy issued a request for proposal for a system which would provide for improved operability, higher accuracy and automated collision avoidance functions. An award was made to Sperry Systems Management for the development of HICANS in December 1977. Three years later, in December 1980, the HICANS system completed its factory acceptance test and was delivered to Key West, Florida for installation aboard the Pegasus. The installation and dockside tests were completed by mid January and were followed by a test and evaluation program which is scheduled to culminate in an OPEVAL in the Fall of 1981.

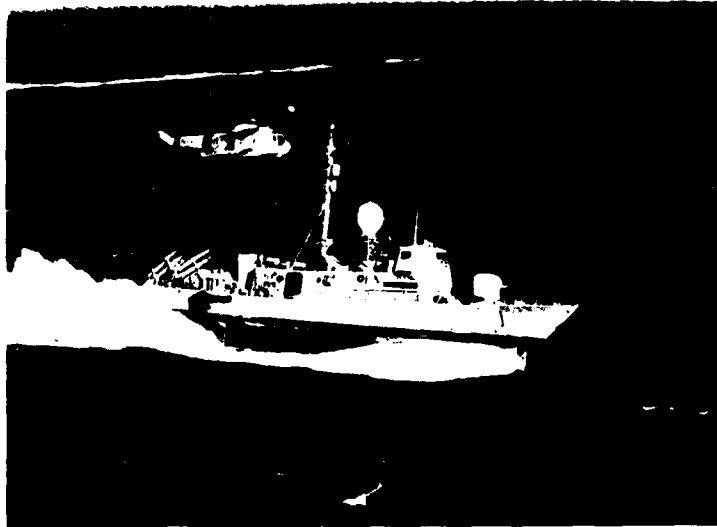


Figure 1. USS Pegasus (PHM-1)

HICANS BACKGROUND

The ship automation program, which eventually led to the HICANS, was started at Sperry in 1968. This program addressed both commercial and high speed ship navigation and collision avoidance. The initial high speed ship studies were sponsored by the Joint Surface Effect Ship Project Office in 1969 and were later applied to hydrofoils as well as surface effects ships.

INCAS (Integrated Collision Avoidance and Navigation System) was the first system developed using high speed ship concepts. It was used for high speed simulations and was successfully evaluated aboard a commercial tanker in 1971 and 72. The first commercial systems were produced by Sperry in 1972 and more than 500 systems have been delivered since then. In support of the Surface Effect Ship programs, a commercial system was modified for use aboard an SES. This system, CAANS (Collision Avoidance and Navigation System), was to be evaluated aboard one of the 100 ton SES'S but because of schedule conflict, was installed and evaluated aboard USS FLAGSTAFF (PGH-1).

The first militarized collision avoidance and navigation system was provided to the U.S. Navy as part of the Integrated Bridge System (IBS)⁽²⁾. The IBS was installed aboard USS McCANDLESS (FF-1084) in 1976 and during nine months of at-sea testing in which the effectiveness of the system was demonstrated, McCandleless participated in two fleet exercises, including a joint U.S.-Canadian exercise, and a modified refresher training in addition to all the normal evaluations of a navy frigate.

Closest Point of Approach (CPA) will be less than the value selected by the operator. In Figure 2, own ship heading marker does not intercept any PPC or PAD, therefore, the ship is on a safe course and all CPA's will be greater than the preset value. If own ship's heading were altered to approximately 290 degrees, then a potential collision threat would exist for target 004. If no PAD exists or if it is not within the screen display area, then a vector representing the target's travel in six minutes is displayed (target 003). This display approach presents a time ordered CPA matrix which allows a operator to determine at a glance the threats to own ship, and to determine a safe course change whenever necessary.

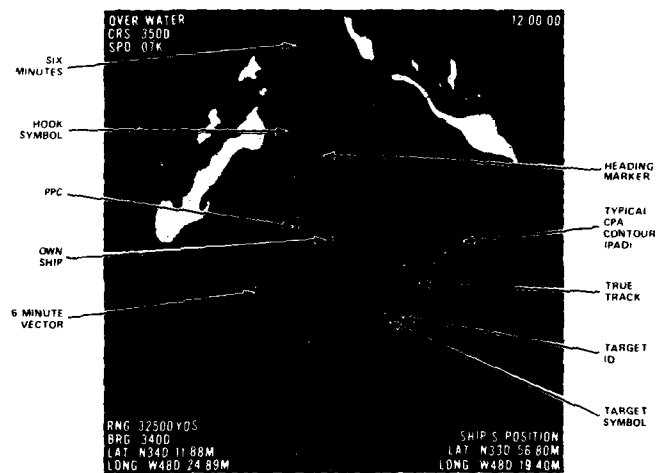


Figure 2. Collision Avoidance Conning Display

To determine the effects of a change in own ship's speed, a trial speed may be entered by the operator and while the trial speed is selected, the conning display is recalculated to reflect this speed.

Figure 3 shows the collision avoidance tableau on the data display. The four most threatening targets are displayed whenever collision avoidance is selected. Additional targets may be displayed using the paging mode of the data display. This data tableau contains all of the data normally obtained by manual plotting.

CONTACT	TGT	BRG	RNG	CRS	SP	BCPA	CPA	TCPA	CPAT
DATA	004	329	21.7K	175	11	263	08.8K	035	1234
	002	148	25.4K	045	06	148	25.4K	000	1200
	003	247	26.1K	153	22	247	26.1K	000	1200

Figure 3. Collision Avoidance Data Display

To alert the operator to potential danger two collision avoidance alarms are provided. The CPA Alert is activated if a target has a CPA less than the preset value and that CPA will occur within 12 minutes. The Minimum Range Alert occurs when a target's actual range is less than the minimum range selected by the operator. These alarms are both audible and visual, and the target data causing the alarm blinks on both the Conning and Data Displays. The audible portion of the alarm may be silenced by pressing the alarm indicator.

Navigation

The HICANS navigation function is addressed primarily to coastal navigation and piloting, and is accomplished by superimposing a nautical chart onto the radar display. The original Navy requirement was for a TV image of a standard nautical chart, however the basic hardware also provided digital chart capability and only required software to allow full evaluation of both techniques.

The system continuously maintains a Dead Reckoned (DR) position based on gyro and EM log inputs. This position is displayed as latitude and longitude readouts and is used by both chart modes. The DR position can be updated using OMEGA fixes when in open ocean and by one of the following when in either of the chart modes:

- Map matching
- Radar position fixing
- Visual position fixing.

These techniques are described in the following paragraphs.

Paper Chart Navigation. For paper chart navigation, a TV camera is used to provide an image of a nautical chart which can be mixed with the radar TV video. Figure 4 shows a typical display of a paper chart image superimposed on the radar. The operator can slew the chart to obtain a match of radar returns with the charted data and from this, the location of own ship with respect to charted hazards is known. The system uses dead reckoning to maintain this alignment. Note that collision avoidance data may also be displayed at the same time providing a complete picture of all hazards for the OOD. In the paper chart mode, the system allows the operator to enter up to thirty (30) navigation aids. These aids are entered by type, latitude, and longitude and appear on the conning display when within the displayed area and as a list on the data display. Having digitally stored navigation aids provides three enhancements to the paper chart mode:

1. Once aligned with the radar and paper chart, the aids provide a reference for quickly realigning the new paper chart when a chart change is necessary. The aids also provide a latitude and longitude reference which is not available directly from the paper chart.

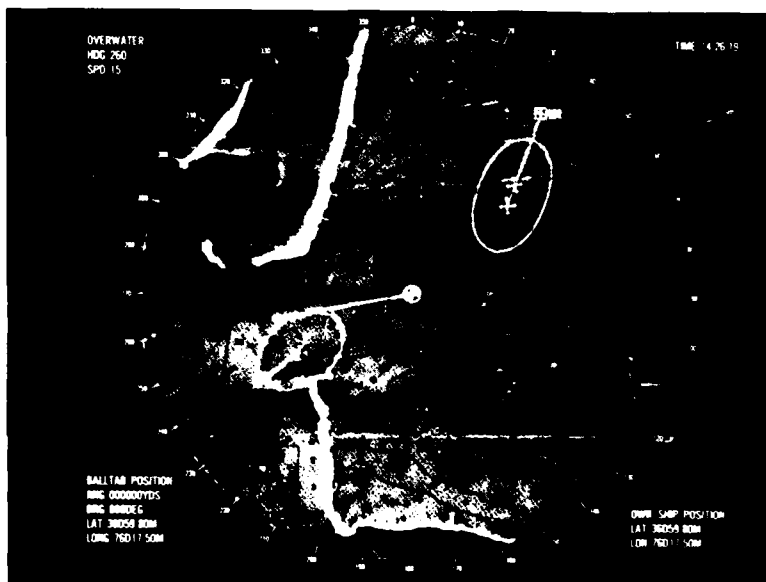


Figure 4. Paper Chart Display

2. If there are radar trackable aids, such as fixed lights (and secondarily buoys), the system will perform automatic radar position fixing. To accomplish this, the operator first aligns the aid symbol with the radar return and then designates these to the system for radar position fixing. The system then tracks the radar return and maintains the alignment of the two. Course and speed of the ship over the ground are also calculated. Set and drift can also be requested by the operator when in radar position fixing. Up to 10 aids may be used at one time for radar position fixing. The system checks for consistency and will not use one or more of the aids if they do not meet the acceptance criteria. If all of the aids fail the test, the system will provide an alarm.
3. Visual lines of position can also be displayed using the digital navigation aids. An operator using either of the two bridge peloruses can enter a sighting into the system; the system will then correlate that bearing with the appropriate aid and display a line of position (LOP) on the conning display. The LOP's are advanced as in a running fix to eliminate timing errors. With two or more LOP's displayed the operator, if necessary, can slew the chart to insert the visual fix. The system will display up to six LOP's at one time.

Digital Chart Navigation. HICANS provides the capability to display chart features which have been loaded into the computer from magnetic tape. The chart consists of selected navigation aids, straight line approximations of shore lines, shoal lines, channel lines, and intended track lines. Figure 5 shows a typical conning display digital chart. On the data display the navigational aids can be called up with amplifying data such as the type of buoy and its number or the type of visual aid.

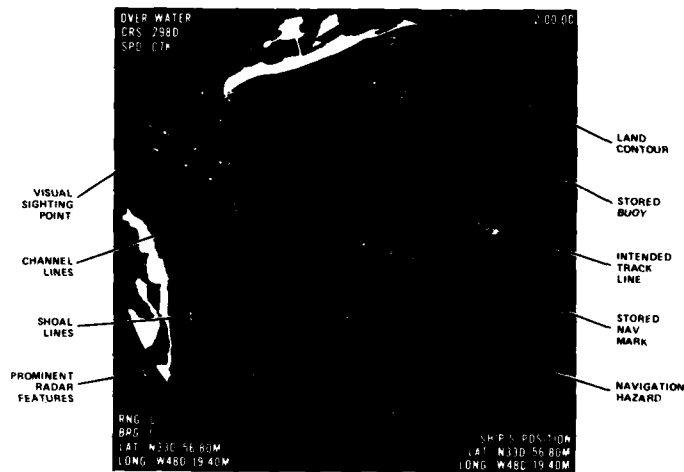


Figure 5. Digital Chart Display
C3-7

The digital chart mode has both radar position fixing and visual lines of position as described for paper chart. In addition, using the intended track line, which can be altered by the operator, the system can provide course-to-turnpoint information, including course and time to turnpoint, next course, and a graphic display of the turnpoint. Because the chart data is stored digitally, there is no calibration required; range scale selection is not limited; and a large area can be covered the reducing the number of times a chart must be changed. The data (e.g., navigation aid numbers) can be selectively filtered to remove unnecessary data from the screen.

Other Features

HICANS also provides assistance to the operator for taking station on a guide. Once a tracked target has been designated as a guide, and station coordinates have been entered by the operator, the system will display a course-to-station based on present ship's speed. If a trial speed is entered, the system will provide the solution using that speed. The solution(s) are displayed both on the conning display and the data display.

For other maneuvers the system calculates a "future maneuver" solution. To obtain this, the operator designates a point on the display and the system recomputes the display to appear as it would if own ship proceeded to that point. As with trial speed, the solution is displayed and updated only as long as the button is held down.

Up to ten (10) waypoints can be entered by the operator. These waypoints are then displayed on the conning display when within the display area.

A video recorder which records the image on the conning display provides a record for legal, event reconstruction, and training purposes.

SYSTEM DESCRIPTION

Operator Stations

HICANS has three operator stations. The CIC Console shown in Figure 6 is the primary station. From this station, the operator can select modes and display configurations, acquire and drop targets, control the digital chart and request course-to-station solutions. Two interswitchable TV monitors are provided along with backlighted pushbutton switches, thumbwheel switches, a trackball, and a numeric keyboard. In USS PEGASUS this console is located in the forward starboard corner of CIC and is readily accessible to the Tactical Action Officer.

The Bridge Console, shown in Figure 7 is located on the left side of the pilothouse and provides the Officer of the Deck with primarily a display function. When the bridge is in control of the system, the operator can select modes and control the display configuration for decision making purposes, but cannot perform functions such as target acquisition or manual tracking. The console contains two switchable TV displays with pushbuttons and a trackball. The bridge operator can use the trackball to request data on targets and navigation aids, and to measure range and bearing (or latitude and longitude). Both the bridge and CIC operators can also select the ship's low light level TV to be displayed on one of the TV's.

The third station consists of a single 17" TV monitor and the controls for the paper chart system. This station, shown in Figure 8, is located adjacent to the chart table and allows the operator to slew the camera into position and to trim the zoom lens if necessary. The camera controls are also accessible from this station.

Equipment Description

Figure 9 shows a block diagram of the HICANS. The center of the system is the AN/UYK-20 computer which is the U.S. Navy standard mini-computer. The software is written in CMS-2M, the standard higher order language for AN/UYK-20. The program and digital charts are loaded into the computer from the AN/USH-26 cartridge magnetic tape unit.

The computer interfaces with the ship's gyro and speed log as well as with the operator controls and indicators through the data converter unit.

Radar target tracking is accomplished by software in the AN/UYK-20 and the hardware video processor. This device, which interfaces with both the AN/SPS-63 navigation radar and the MK 94 fire control radar, contains circuitry for two trackers and one guard ring. The guard ring hardware is shared between the two guard rings under computer control and the trackers are also assigned by the computer. The computer provides gate size and location to the tracker and the tracker returns radar noise level and target centroid to the computer. From this, the computer adjusts thresholds and determines target position. This data is then smoothed by an alpha-beta filter for computation and display of target vectors and danger zones.

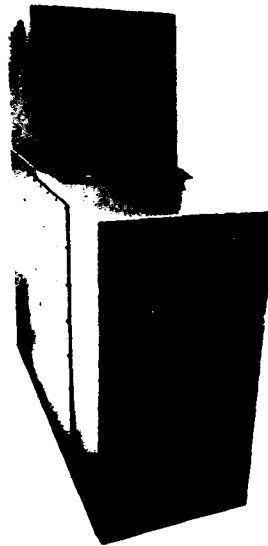


Figure 8. Paper Chart Control Station
C3-10

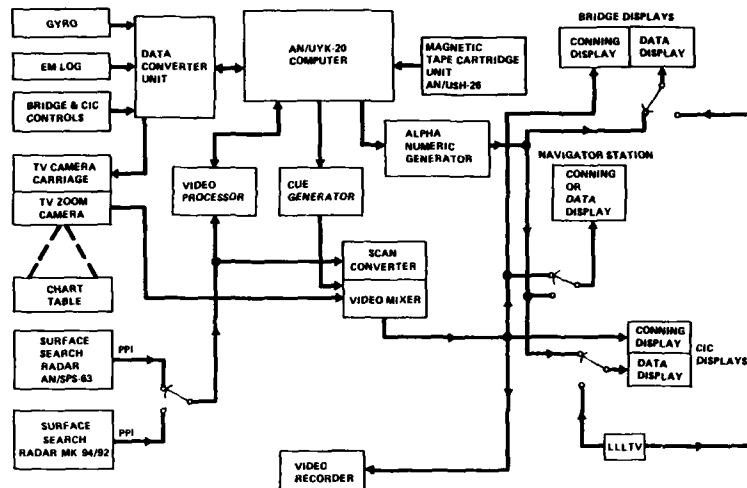


Figure 9. HICANS Block Diagram

HICANS uses raster scan TV for the operator displays. TV was chosen because of the brightness available with TV and the ease of providing additional displays. To provide sufficient resolution for the graphic display, high resolution (945 line) TV is used. The HICANS TV monitors are 14 and 17 inches with sufficient brightness to be viewable in the high ambient brightness of the pilothouse. The monitors automatically sense the line rate (945 or 525) of the incoming signal and switch to that rate.

The radar scan converter provides the TV display of radar for HICANS. This digital device takes the radar data in standard PPI format, digitizes it into seven shades of grey and stores it in memory. The memory is then read out in X-Y format at the TV line rate. The data is decayed digitally with a fade from 1 scan to 16 scans.

Computer data for the conning display is converted to high resolution TV format by the cue generator. This digital device using the on-the-fly technique generates vectors, circles, ellipses, alphanumeric and special symbols, including NTDS symbology.

The cue generator data and the paper chart TV camera data are mixed with the scan converted radar data in the video mixer portion of the scan converter and provided as buffered outputs to each of the HICANS monitors. The scan converter also generates the TV synchronizer signals for the three high resolution devices.

An alphanumeric generator provides data for the data display in a 525 line TV format. This device produces 24 lines of 80 characters from computer provided data.

The paper chart image system (shown in Figure 10) consists of a 945 line TV camera with 10 to 1 zoom lens and an X-Y carriage system. The camera system covers a field of view to provide a circular TV picture of a nautical chart to match the scan converted radar. Zoom commands for the lens come from the computer via the carriage electronics. The computer calculates the zoom command based on the operator entered chart scale and the selected display range scale. Although the selection of range scales is limited, generally at least three are available. For example, for a 1: 40,000 chart, range scales of 1, 2, and 4 miles are available. The camera head and zoom lens are mounted on the X-Y carriage. This carriage is moved by stepper motors driving lead screws; position of the carriage is sensed by synchros. The carriage electronics accepts X-Y position commands from the computer and drives the camera to the ordered position. The carriage control station allows the operator to slew the camera and also to make trim adjustments to the X and Y position using a trackball. The zoom lens can also be trimmed by the operator. A backup manual mode allows the operator to control the X-Y position and camera zoom directly.

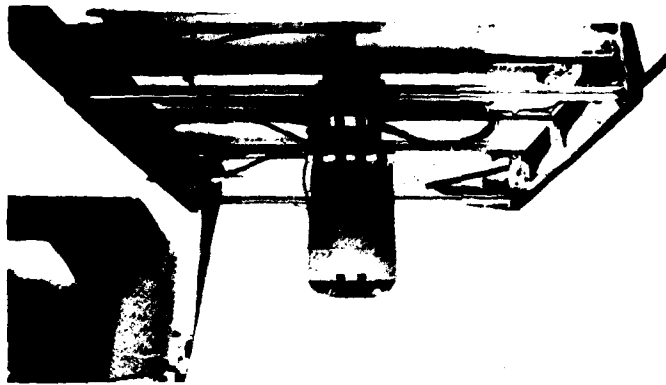


Figure 10. Chart Image System

TESTING

The assembly and integration of HICANS was completed in the fall of 1980. Prior to delivery, Navy personnel from the USS PEGASUS and the Mobile Logistic Support Group received training on the operation and maintenance of the system. The system was delivered to the PEGASUS in December, 1980.

Installation and checkout of HICANS in PEGASUS was accomplished pierside at Key West, Florida in a three-week period and at sea test and evaluation began in the middle of January. Since the installation, HICANS has been PEGASUS's primary coastal navigation system.

From January through August of 1981, PEGASUS has been at sea for approximately 30 days and has participated in one fleet exercise. The Technical Evaluation (TECHEVAL) has just been completed; and although analysis of the data is still being performed, early indications are that the testing has been very successful. For example, for one transit into Key West, the mean error was 25 yards compared with the specification goal of 50 yards.

FUNCTIONAL EXPERIENCE

Most of the piloting experience with HICANS has been in and out of Key West. With both the digital and paper charts available, the ship normally uses the digital chart with regular shifts to the paper chart for confirmation of position. The positions have usually been in close agreement and are in agreement with the visual location on the ranges of the channel. A typical comparison has been HICANS shows the ship slightly to one side of the center of channel, while a sighting on the range shows the ship slightly to the other side. Visual position fixing, map matching, and radar position fixing are all being used with consistent success, and on at least one occasion a simulated "blind" entry was made using only HICANS. On a transit up the coast of Florida to Mayport, the paper chart (with manually entered digital aids) was used throughout the trip. When approaching the entrance to Mayport, the CIC used HICANS to talk the bridge into port.

During the fleet exercise HICANS was used extensively in allowing USS PEGASUS to perform its mission. The course-to-station solution was used several times and the continuously updated collision avoidance picture not only provided for safe maneuvering, but it allowed Pegasus to easily maintain the identity of the other ships and in one case under severe weather conditions, to establish the identity of the underway replenishment (UNREP) ship based on the stated UNREP course and speed.

During normal operations, the CIC console is operated by the ship's First Class Operations Specialist and the Officer of the Deck uses the bridge console. On many occasions the Executive Officer who has received no formal training on HICANS has operated the system in his capacity as navigator. Based on their experience with HICANS to date the crew has been very positive in their acceptance and use of the system.

RELIABILITY AND MAINTAINABILITY

Between the middle of January and the middle of August, the HICANS has accumulated 1750 hours. During this period there have been only three critical failures where a critical failure is defined as one which does not allow HICANS to perform one or more of its functions. This results in an observed Mean-Time-Between-Failures (MTBF) of 583 hours. This compares favorably with the predicted value of 570 hours and if maintained during the remainder of the

at-sea testing, will more than satisfy the threshold of 370 hours. Three other failures, which are considered minor because they did not degrade of HICANS performance, have also occurred.

Maintenance to date, including isolation and repair of the above failures has shown both preventive and corrective maintenance are easily performed. A maintenance demonstration has been conducted aboard PEGASUS, and the measured mean-time-to-repair (MTTR) was approximately 35 minutes compared with a goal of 60 minutes. Technical manuals have been provided and are being verified as the system is being operated and maintained.

FUTURE PLANS

HICANS is scheduled to undergo formal Technical Evaluation (TECHEVAL) and Operational Evaluation (OPEVAL) in the fall of 1981. Based on experience to date, this testing will be successful and the system will be approved for service use. Additional systems may then be built for the five additional PHM's which have been ordered by the Navy.

In conclusion, HICANS is proving to be a reliable, functionally capable system which should increase the effectiveness and safety of the PHM's. It is also an already developed system ready for use on other high speed ships.

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SENSING SYSTEMS FOR MEASUREMENT AND CONTROL OF RELATIVE SHIP POSITION
OVER CLOSE RANGES (UNDERWAY REPLENISHMENT)

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ABSTRACT

The probability of ship collision during underway replenishment (UNREP) operations increases with decreasing distance between the ships. The strong interaction forces and moments between ships steaming alongside can make UNREP more risky than normal cruising. As a result, analysis has been performed to identify the ship control parameters and their allowable limits pursuant to reducing the probability of collision. The David Taylor Naval Ship Research and Development Center (DTNSRDC) is now developing a system to measure and display the critical control parameters for the helmsmen of both ships during UNREP. Both active and passive sensors were considered for the system measurement unit, with acoustic and electromagnetic sources. Candidate sensor systems were compared on the basis of cost and performance, mainly in the areas of accuracy, resolution, safety, alignment difficulty, and update capabilities. Several basic geometrical configurations were also studied, ranging from a simple single beam system to the more complicated closed-X, four-beam configuration. From the results of this investigation, it was concluded that an active millimeter wave system operating in the closed X configuration would best satisfy the Navy's needs under the cost and performance constraints. Passive systems were not found to be as well developed as active systems but offer good promise as candidate ship control sensors. Additional program plans include the development of ship controller and display hardware for evaluation on a hybrid computer simulation at DTNSRDC and at sea on U. S. Navy ships.

INTRODUCTION

The measurement and control of ship position and motion, during close range maneuvering with another cooperating ship, is the subject of this paper. Most of the information given here was generated for an ongoing project at the David Taylor Naval Ship Research and Development Center; the objective of the project is to provide improved ship control during underway replenishment (UNREP). The ship control aspects are briefly discussed in this paper and in more detail in a related paper.⁽¹⁾

The instrumentation technology used to remotely measure position and motion is generally a function of range, with systems capable of making measurements over thousands of kilometers differing from those making measurements below one meter. The application for close range ship maneuvering falls in range of thousands of meters. For the UNREP application the range of interest is from 50 to 2000 feet.

Instrumentation considered for the measurement of ship to ship separation distance and relative orientation is listed in Table I. Each of the instrument technologies listed has either associated off-the-shelf equipment available or has been proposed as a low risk, although sometimes expensive, development.

Table I. Instrument Techniques for Measuring Distance During UNREP

<u>Energy Form</u>	<u>Active</u>	<u>Passive</u>
Electromagnetic	Radar Millimeter Infrared Visible	Infrared Visible
Acoustic	Ultrasonic (Underwater & Airborne)	Sonic (Underwater)

The measurement of range with an active system is accomplished by measuring the round trip transit time to the target and back. This is instrumented with both pulse systems and continuous wave (CW) modulation. Use of passive techniques to measure range nearly always involves triangulation and geometry to calculate distance.

Electromagnetic energy has been used for distance measurement in nearly every region of the spectrum with the most highly developed active systems using the radar frequencies (30 MHz to 30 GHz). These radar ranging systems vary from extremely sophisticated, expensive systems to the more simpler types such as police radar. They enjoy the advantages of a highly developed technology, readily available components and low absorption in the atmosphere.

The use of millimeter wave frequencies (30 GHz to 300 GHz) to measure distance is a rapidly developing area due to the increasing availability of high frequency solid state components. Current applications are mostly in the field of communications. Advantages of millimeter wave technology are smaller components and low background signals. Operating frequencies can be selected for high atmospheric absorption so that the ship's electromagnetic signature will not be increased.

The design of active systems to measure distance using the infrared and visible frequencies, usually requires narrow beam laser sources which must be aimed in moving-vehicle and moving-target applications. Ranges measured by this method vary from interplanetary distances to sub-millimeter distances. Surveying instrumentation working over several kilometer ranges are available off the shelf. Advantages of using the infrared and visible frequencies include high accuracy and portability of instrumentation. Sources can be selected for both very high and very low atmospheric absorption.

Passive range measuring systems using electromagnetic energy normally operate in the infrared and visible regions. Operation often depends on some form of triangulation involving a target of known dimension. Distances measured vary from the several kilometers to the sub-meter range. The major advantage of passive electromagnetic systems is that the ship's signature is not increased. Disadvantages include a relatively high system cost per unit, low accuracy, and operating difficulty in bad weather.

Acoustic energy can be used to measure distance in many of the same configurations as electromagnetic energy and can be instrumented with either water or air as the energy propagation medium.

Active acoustic range measuring systems usually operate at frequencies below one megahertz and employ some scheme of measuring acoustic energy transit time from source to target and return. The carrier frequency can be selected for both large and small transmitting medium absorption. Disadvantages are that accuracy

is significantly affected by temperature and other transmitting medium conditions and time update of the measurement is very slow relative to electromagnetic systems. Very few acoustic range measuring systems are available off the shelf.

Passive acoustic range sensors have not been developed and are not expected to have performance characteristics competitive with passive electromagnetic systems.

Inertial systems (passive) are also available for distance sensing. In general, the available systems were designed to be complex inertial navigation systems with multiple outputs including up to three-dimensional distance, velocity, and acceleration (both linear and rotational). Distance obtained by integrating acceleration and velocity always contains time dependent errors. When using inertial systems to measure distance it is essential to obtain both accurate initial position and reset data. Inertial systems were not considered for the UNREP application.

UNREP SHIP SEPARATION MEASUREMENT PROBLEM

Underway replenishment in the U. S. Navy occurs in three phases: approach, station-keeping, and breakaway. The approximate paths followed by each ship are shown in Figure 1. During the approach phase, the lead ship (also called supply ship or replenishment ship) sets a constant course and speed and the approach ship (also called tracking ship or receiving ship) comes up from an offset astern position in a straight line approach. The Conning Officer of the approach ship maintains 5 to 8 yards between the wakes during the approach phase; this brings the approach ship alongside the lead ship with a side-to-side separation of about 100 feet. During the station-keeping phase the tracking ship matches speed with the lead ship and maintains a constant separation distance while fuel, goods, and materials are transferred from the lead ship to the tracking ship. Breakaway is accomplished by increasing the speed of the tracking ship above the UNREP speed while slowly turning away from the lead ship. Alternately, breakaway is sometimes accomplished by turning away at very low relative heading angles and drifting outward from the lead ship before increasing speed.

Control of the tracking ship is the responsibility of the Conning Officer who is on the bridge wing and gives orders to the Helmsman and the Lee Helmsman to control the ship's heading and speed. Figure 2 shows a view from the lead ship to the approach ship; the Conning Officer and Commanding Officer can be seen on the bridge wing immediately above the letters D C E.

Sensory inputs to the Conning Officer originate in basically three sources; own ship's measurements, information from sensors rigged especially for the UNREP evolution, and the Conning Officer's feel for the situation or "seaman's eye," (which is very much a function of training and experience). A list of the sensory inputs to the Conning Officer is shown in Table II.

Table II. Sensory Inputs to Conning Officer During Underway Replenishment

<u>Functional Input</u>	<u>Instrument</u>
Ship's Heading	Gyro compass and seaman's eye
Ship's Speed	EM Log and ordered speed
Bearing to supply ship	Pelorus
Range to supply ship	Stadimeter
Lateral separation distance	Phone distance line
Rudder angle	Rudder angle indicator
Sea state	Seaman's eye
Stern wake	Seaman's eye
Rig dynamics	Seaman's eye
Differential speed	Seaman's eye

C4-3

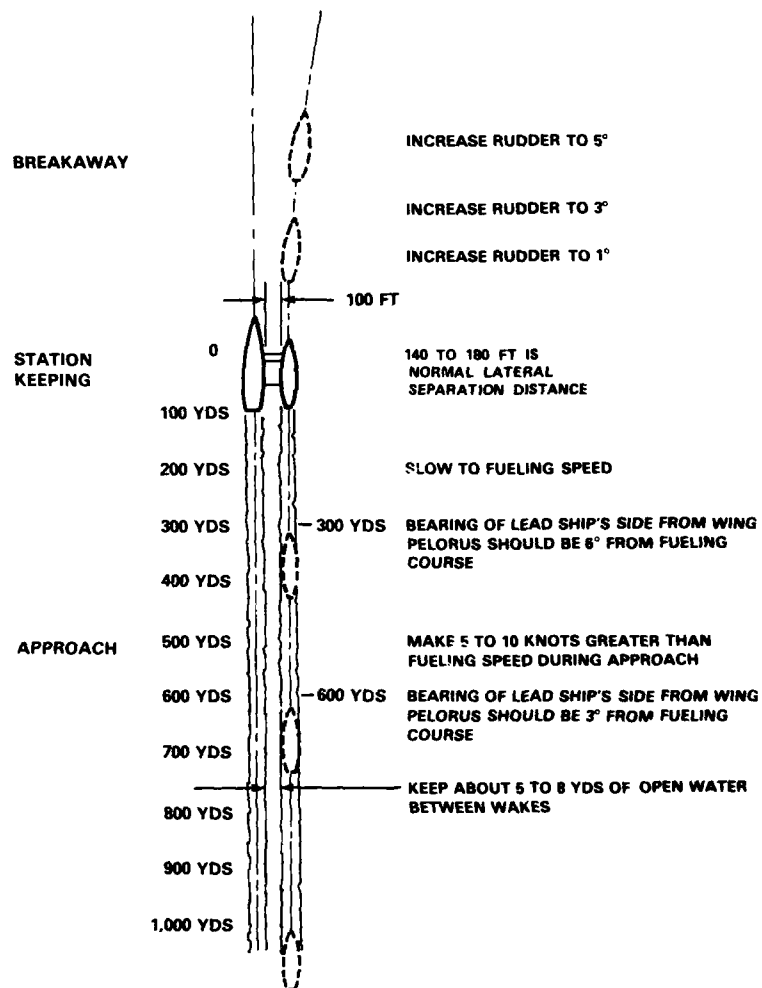


Figure 1 - Approach Path for UNREP

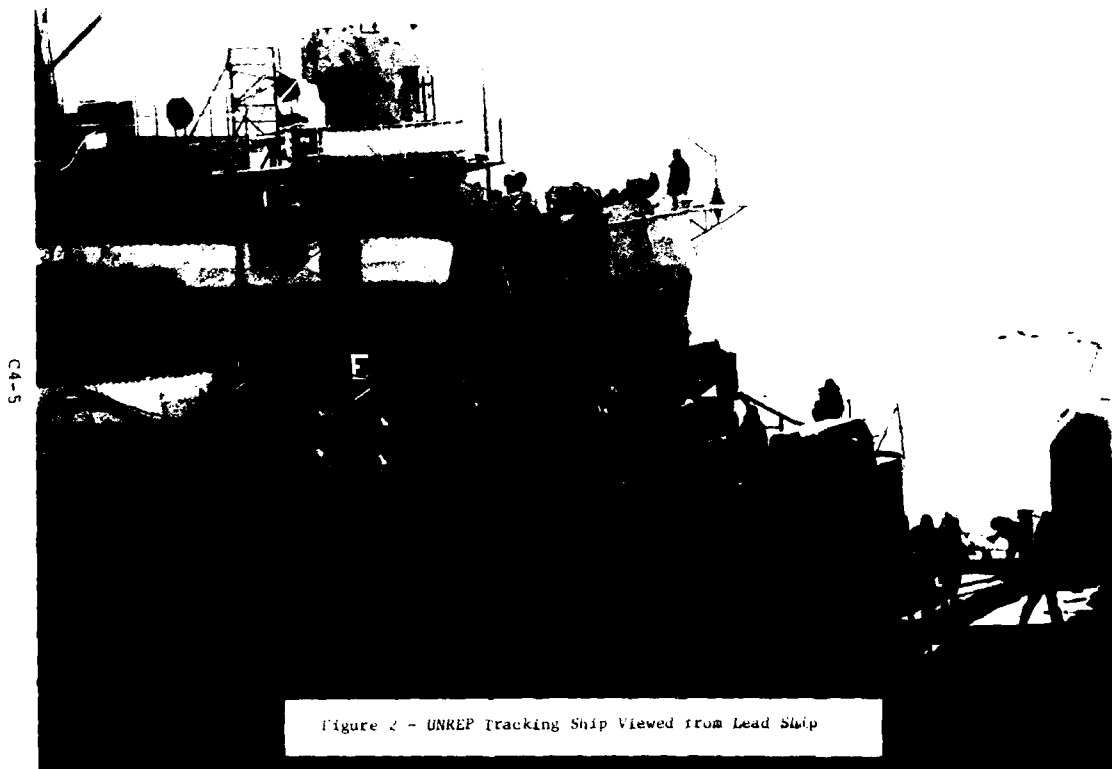


Figure 2 - UNREP Tracking Ship Viewed from Lead Ship

Availability of all this information on the bridge wing varies from ship to ship in the U. S. Navy. The pelorus and stadimeter are used only during the approach phase due to range/accuracy limitations. After the tracking ship comes alongside, the phone distance line is rigged between the two ships and kept taut by crew members. Distance marker flags hung at twenty-foot intervals on the bridge-to-bridge phone distance line allow the Conning Officer to see the separation distance and to estimate the rate of change by counting the flags and observing how fast they pay in or out over the rail.

Instrumentation has become available that can remotely measure the separation distance and relative heading of the approach ship and present more accurate information to the Conning Officer on the bridge wing. Data show that most of the ship control related accidents associated with UNREP maneuvers occur during the approach and station-keeping phases. Approach and station-keeping can be especially difficult to accomplish at night and in bad weather because of the reduced visibility. Ships operating personnel must be more vigilant during UNREP and may become fatigued during long UNREPS. For these reasons, the U. S. Navy has embarked on a development program to improve the information displayed to the Conning Officer and Helmsman and to improve the ship control capabilities through the development of both display-aided manual control and automatic ship control.

Exploratory Simulation Program

The David Taylor Naval Ship Research and Development Center has completed an exploratory development effort that has provided a theoretical basis for a ship control system for the approach ship by means of mathematical analysis and a hybrid computer simulation of two ships during all phases of the UNREP evolution.⁽²⁾ This simulation effort demonstrated ship controllability during close range passing maneuvers and has been used to establish performance specifications for both the ship separation sensor and the ship control/display system.

Every effort in the exploratory development at DTNSRDC centered around the development of a hybrid computer simulation.^{(2),(3),(4),(5)} Nonlinear surge, sway, and yaw equations were used to model two Mariner Class ships conducting a passing maneuver. Both regular and irregular sea states (Pierson-Moskowitz spectrum) were used with a 30-degree oblique seaway (off the port bow). Manual, quickened manual, and automatic steering control were evaluated. The quickened manual control system presented actual rudder angle and recommended rudder angle to the Helmsman, who then acted as a delay and amplifier and matched the two displayed parameters. The simulation block diagram for quickened display control used in the exploratory development program is shown in Figure 3. Operation in the automatic mode eliminated the display and Helmsman, the sum of the controller output and the set point being connected directly to the rudder.

The steering control law used in the exploratory development simulation selected by Alvestad, Brown, and Dimmick^{(2),(3),(4)} was:

$$\Delta\delta = K_1(\Delta\psi) + K_2 \dot{\psi} + K_3 \ddot{\psi} + K_4 (\Delta B) + K_5 \dot{B} + a_t / \Delta B \, dt$$

where

$\Delta\delta$ = rudder order from the automatic controller.

$\Delta\psi$ = yaw, relative to the lead ship (yaw difference from the set point in ground coordinates).

$\dot{\psi}$ = yaw rate.

$\ddot{\psi}$ = yaw acceleration.

ΔB = difference in lateral separation from the desired value.

\dot{B} = lateral separation rate.

a_t = gain constant of the integral control loop.

t = time

K_1, K_2, \dots, K_5 = feedback gain constants.

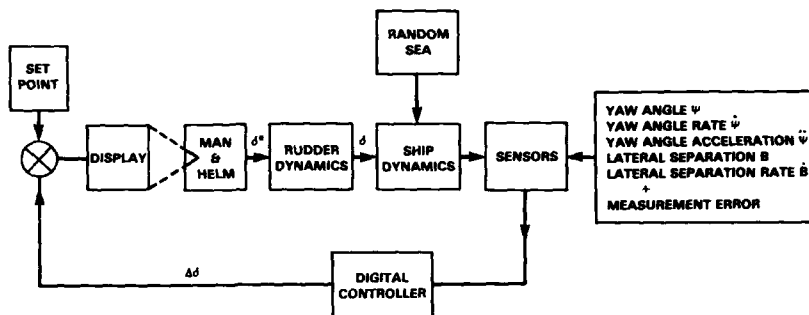


Figure 3 - Simulated Quickened Display Block Diagram⁽⁵⁾

The major conclusions of the exploratory development program at DTNSRDC were:⁽²⁾

- o Parameters required for ship control during close range passing maneuvers are lateral separation, lateral separation rate, longitudinal separation, longitudinal separation rate, relative heading, and relative heading rate.

- o First-order sea state excitations dominate the UNREP steering problem in severe sea states.

- o Update intervals should be once per second or faster to maintain lateral separation control within 20 feet of the set value using automatic or quickened manual control in severe sea states.

- o Quality of the steering control could be improved by redesigning the controller used in the simulation. (The control law is presently being refined as discussed in a related paper at this conference.⁽¹⁾)

- o Quickened manual steering control shows promise for use on the approach ship during UNREP but requires additional study and human factors experiments (presently being done).

- o Noise and measurement errors of about 3 percent in the maneuvering control variables (separation distance and relative yaw) are acceptable for the conditions of the simulation.

Advanced Development of the Ship Separation Sensor and Controller

From the results of the exploratory development program at DTNSRDC, a strategy was evolved for additional effort, which is presently funded and ongoing. The objective is to develop a hardware package for Navy fleet use via the following approach:

- o Develop and evaluate an experimental model of a ship separation sensor.
- o Develop and evaluate an experimental model of a ship separation controller.
- o Complete an advanced development model improved by "lessons learned" in the first two steps. A block diagram of the experimental models of the sensor and controller is shown in Figure 4.

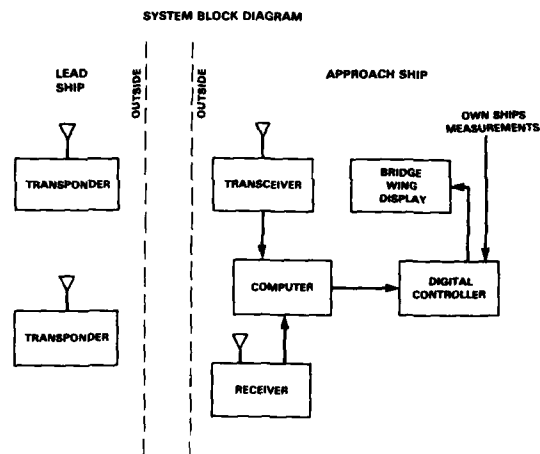


Figure 4 - Block Diagram Close Range Ship Controller and Sensor

Specifically, an experimental model of the sensor will be developed to remotely measure the parameters required to adequately control the lead ship:

- o lateral ship separation and rate
- o longitudinal ship separation and rate
- o relative yaw and rate

(The first two listed parameters may also be formatted as range and bearing and their rates). Outputs of the sensor will be displayed on the bridge wing. Evaluation of the sensor will include calibration over land and water and technical performance evaluation onboard ship by engineering personnel. The sea evaluation will proceed independently from the controller development. Sensor development is presently underway and is the primary subject of the remainder of this paper.

The experimental model of the ship controller and display system will be developed to provide tracking ship speed control and steering control in the manual, display-aided (quicken) manual, and automatic modes. The manual mode will

include filtering of the sensor outputs for ship's motions. The display-aided manual control will include two options: a quickened display of heading to the Conning Officer on the bridge wing and a quickened display of rudder angle to the Helmsman. The bridge wing display will require inputs by the Conning Officer to select one or more of the following: approach speeds, longitudinal distance, and lateral separation distance. The controller will be designed for operation in all three phases of UNREP: approach, station-keeping, and breakaway.

A six-degree of freedom simulation is being developed and will be implemented on a hybrid computer facility at DTNSRDC. The simulation will be used initially to evaluate the controller performance on Navy destroyers and supply ships. The controller is being developed⁽¹⁾ for all classes of U. S. Navy ships that perform UNREP. The controller will be evaluated at sea onboard Navy ships by engineering personnel.

Specific plans for the advanced development model of the close range ship control system for UNREP are not detailed at this time. However, all design deficiencies discovered in the experimental models will be corrected and appropriate design improvements will be made. The hardware package will be designed for use by sailors in the shipboard environment.

The ship separation sensor development is a vital phase of the UNREP program, for if the sensor cannot be made to perform with sufficient accuracy, the remainder of the program will have nothing upon which to build. The sensor problem is complex, involving several technical trade-offs and interactions. The remainder of this paper will therefore be concerned primarily with the sensor development phase of the UNREP program.

Ship Separation Sensor Performance

The ship separation sensor is being designed to measure two components of ship separation distance (longitudinal and lateral), relative heading of the approach ship with respect to the lead ship and to calculate their rates. The separation distance set points are either held constant or changed at a controlled rate. The relative heading and rate are not set to given values but provide the earliest indication that a ship control problem might develop. The specified performance of the ship separation sensor is summarized in Table III.

Table III. Ship Separation Sensor Performance Specification Summary

Parameter	Allowable Limit
Separation Range	50 to 2000 feet
Separation Range Accuracy	± 4 feet or $\pm 3\%$ of Reading
Separation Rate	-25 to +25 feet/second
Separation Rate Accuracy	± 0.5 feet/second
Relative Heading	-20 to +20 degrees
Relative Heading Accuracy	± 0.5 degrees
Relative Heading Rate	-20 to +20 degrees/second
Relative Heading Rate Accuracy	± 0.5 degrees/second
Safety	Direct Beam Personnel Safe
Ship Signature	Not increased
Update Time	Once/second
Environmental	All weather Salt spray Shipboard vibrations
Sensor Configuration	Minimum number of units
Sensor Alignment Stability	± 10 degrees roll
Sensor Tracking	Automatic
Electromagnetic Compatability	With all other ship systems

All data given in Table III reflect performance needed in a final shipboard system except the following: the sensor alignment stability specification will be increased to $\pm 30^\circ$ roll and maximum performance limits will be established for pitch, yaw, heave, surge, and sway. The ship's roll is the greatest source of apparent sensor error. The controller will contain filtering that compensates for roll-induced sensor output variation. The final sensor hardware package will also include shock and vibration requirements for the shipboard environment.

The approach used in the UNREP program was to issue a sensor performance specification, invite proposals, and award a contract to industry based on greatest benefit to the Navy. The winning technology was a ranging system based on millimeter wave technology as explained in a later section of this paper. At the time of this writing, hardware has not been delivered.

SENSOR CONFIGURATIONS

The possible combinations of sensor units into various shipboard geometrical configurations are too numerous to cover adequately. However, after some number of sensors units have been installed, the addition of further units will only lead to redundancies and to confusion in the interpretation of results. This section will examine the simpler configurations of sensors that will provide sufficient information concerning ship variables determined to be critical (1), (2) during ship control maneuvers. These variables are lateral separation (B), lateral separation rate (\dot{B}), relative heading angle (ψ), and relative heading angle rate ($\dot{\psi}$). In addition, longitudinal separation (A) and rate (\dot{A}), and bearing (θ) will be measured or computed.

In some configurations more than one lateral and longitudinal separation are calculable from the measured distance quantities because of the number of sensors and the fact that the ships are not on exactly parallel paths. Each of the separations (and their rates) are given with the understanding that the shorter lateral separation represents the closest calculated distance between ships and that the separate distance measurements can be mathematically combined for averaging, for error reduction, or for redundancy.

Several assumptions were made before analyzing the chosen geometrical configurations and deriving the formulas for the critical variables. These assumptions are given below.

1. It is assumed that the sensors are part of a final ship control system that automatically compensates for ship motions that otherwise would introduce apparent errors into the displays.
2. It is assumed that all of the sensors lie in a single plane and that this plane is parallel to the surface of the water. Compensation for deviations from this assumption will also be done in the electronic computer portion of the final system.
3. It is assumed that all sensors on each ship are mounted on the sides of the ship, at the most outboard points, and that these points are equidistant from the ship centerline. This makes lateral separation equal to side-to-side separation and makes the line through the sensors on each ship parallel to that ship's centerline.
4. It is assumed that the rates for each variable can be electronically obtained as the difference of two consecutive measurements or computations divided by the time between them, or some other similar technique.
5. It is assumed that all measurements are taken at intervals short enough to enable a final system to meet any update requirements.

The formulas presented below are the results of only one method of determining the variables. Other choices of angles, coordinate systems, etc. will lead to different formulas for the variables. The formulas may not even be in the simplest form, but are presented to demonstrate that methods exist for determining the critical variables in the two-ship scenario. Equipment fabricated for the development program at DTNSRDC will not be constrained by the above assumptions.

"I" Configuration

The "I" configuration is shown in figure 5. It is a single beam system that provides information regarding the relative position of the lead ship with respect to the approach ship. More information than just simple distance (slant range) is needed to provide the capability of determining all the required critical variables. The system must also measure the angles between the beam and the respective ships' headings, labelled as α and γ in figure 5. One method for obtaining these angles is to have angle pick-offs on the unit mounts. The angles are electronically coded and sent to the approach ship system computer for processing. Another method is to sweep the beam through an arc that covers the other ship and electronically determine the angle to the other sensor when a return beam is sensed. Heading angle information obtained from the lead ship gyro can also be coded and sent over the sensor beam. An advantage of a single beam configuration is that it is relatively easy to locate the transceivers on each ship so that there is very little probability of interference by UNREP lines, cargo, etc. that could temporarily block the beam. The system is also a lower cost system, needing only one transceiver on each ship. Another advantage is that the mathematics of the configuration is relatively simple and therefore the system requires a computer with relatively simple computational capabilities.

A major disadvantage of the "I" configuration is that lateral separation, a direct indicator of operational safety during UNREP, is not a function of α . Therefore, rotation of the approach ship about a point at or near its transceiver would not cause a perceptual change in the lateral separation display until the ship responded. Valuable time could be lost, resulting in a higher probability of mishap. Conning Officers would need to be trained to observe and interpret the relative heading display as well as the lateral separation display.

"V" Configuration

The "V" configuration, shown in figure 5, is a dual beam system emanating from a single station on the approach ship. Two targets on the lead ship are separated by a known distance, d . To be able to determine all of the critical variables this system must measure the angle between the approach ship heading and one of the beams.

The cost of this type of system is also relatively low since no lead ship attitude information needs to be transmitted back to the approach ship and since there is only one transceiver on the approach ship. However, with two beams the probability of beam interference caused by UNREP lines, cargo, etc. is greater than the one-beam "I" configuration. Also, as in the "I" configuration, rotation about the approach ship sensor does not immediately affect lateral separation so that display interpretation training must be provided.

"II" Configuration

The "II" configuration, shown in figure 5, is also a two beam system, but uses two transceivers on the approach ship and two targets on the lead ship. Each pair of points is separated by known distances (d_1 and d_2). As in the two previous configurations, the angle between the approach ship heading and one of the beams must be measured to determine all of the critical variables. Otherwise, the

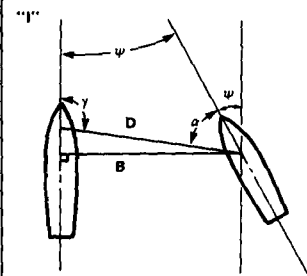
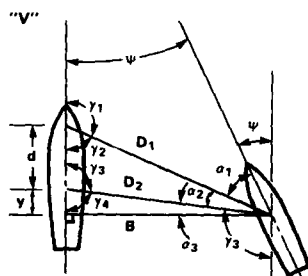
		
MEASURED → CALCULATED ↓	D, α, γ	D_1, D_2, d, α_1
LATERAL SEPARATION	$D \sin \gamma$	$D_2 \cos \alpha_3$
LONGITUDINAL SEPARATION	$D \cos \gamma$	$d_1 + y$ or $D_1 \sin (\alpha_2 + \alpha_3)$
RELATIVE HEADING	$180 - \alpha - \gamma$	$90 - \alpha_1 - \alpha_2 - \alpha_3$
BEARING	α	α_1
OTHER FORMULAS		$\alpha_3 = \gamma_3 - 90$ $\gamma_3 = \cos^{-1} \left[\frac{d_1^2 + D_2^2 - D_1^2}{2d_1 D_2} \right]$ $\gamma = D_2 \sin \alpha_3$ $\alpha_2 = \cos^{-1} \left[\frac{D_1^2 + D_2^2 - d_1^2}{2D_1 D_2} \right]$

Figure 5 - Close Range Ship Control Study Configurations

MEASURED → CALCULATED ↓	$D_1, D_2, d_1, d_2, \theta$	D_1, D_2, D_3, d_1, d_2
LATERAL SEPARATION	$B_1 = D_1 \sin \alpha_1, B_2 = D_2 \sin \alpha_2$	$B_1 = D_1 \sin \alpha_1, B_2 = D_2 \sin \alpha_2$
LONGITUDINAL SEPARATION	$A_1 = D_1 \cos \alpha_1, A_2 = D_2 \cos \alpha_2$	$A_1 = D_1 \cos \alpha_1, A_2 = D_2 \cos \alpha_2$
RELATIVE HEADING	$\alpha_2 - \alpha_1 \text{ or } \alpha_1 - \theta$	$\alpha_2 - \alpha_5$
BEARING	θ	$\alpha_1 - \psi$
OTHER FORMULAS	$\alpha_2 = \cos^{-1} \left[\frac{D_1^2 + d_2^2 - D_2^2 - 2D_1d_2 \cos \theta}{2D_2d_1} \right]$ $\alpha_3 = \sin^{-1} [D_1 \sin \theta / R]$ $R = [D_1^2 + d_2^2 + 2D_1d_2 \cos \theta]^{1/2}$ $\alpha_4 = \sin^{-1} [d_1 \sin \alpha_2 / R]$ $\alpha_1 = \theta + \psi = \theta + \alpha_2 - \alpha_3 - \alpha_4$	$\alpha_1 = \cos^{-1} \left[\frac{D_1^2 + d_1^2 - D_2^2}{2d_1D_1} \right]$ $\alpha_2 = 180 - \alpha_3 - \alpha_4$ $\alpha_3 = \sin^{-1} (B_1/D_3)$ $\alpha_4 = \cos^{-1} \left[\frac{D_2^2 + D_3^2 - d_2^2}{2D_2D_3} \right]$ $\alpha_5 = \cos^{-1} \left[\frac{D_2^2 + d_2^2 - D_3^2}{2D_2d_2} \right]$

Figure 5 (continued)

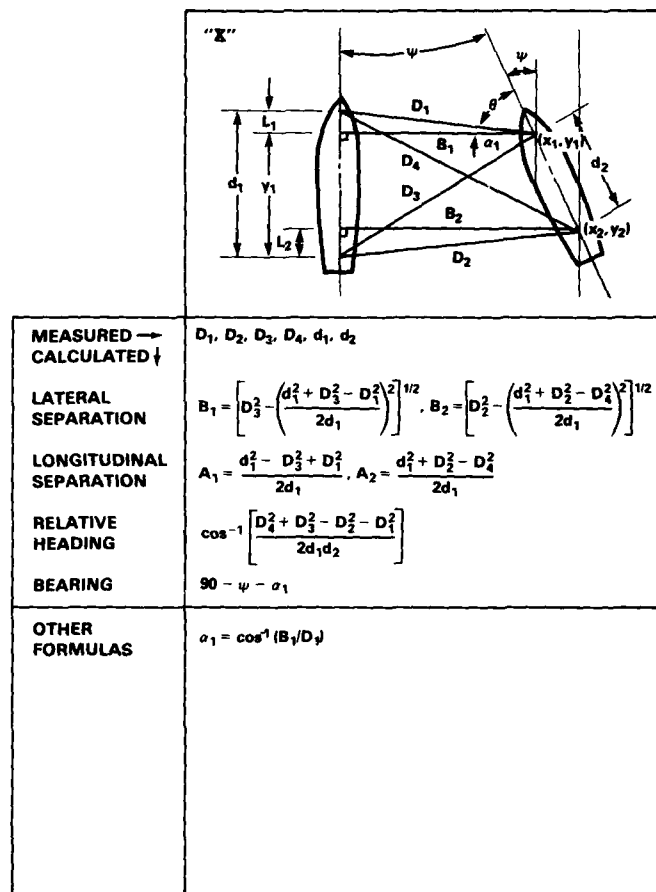


Figure 5 (continued)

resulting quadrilateral could distort about any side without changing any of the sides' lengths, thus causing the variables to be indeterminant.

The mathematics of this configuration begin to get tedious, but are no problem for today's desk top computers. The cost of this system, however, is greater than for the two previous configurations since the total number of units has increased to four.

The probability of beam blockage is lower than for the "V" configuration because one transceiver-target pair can be located forward of the UNREP rigging and the other pair located aft of the rigging.

"Z" Configuration

The "Z" configuration, shown in figure 5, is similar to the "II" configuration. It, however, also measures one diagonal distance, D_3 , which solidifies the quadrilateral and eliminates the need to measure any angles. All angles and therefore all of the critical variables can be calculated from the two known distances (d_1 and d_2) and the three measured distances (D_1 , D_2 , and D_3). The increased cost of having to measure D_3 will be at least partially offset by not having to measure any angles. The disadvantage of the system is that beam D_3 must pass fore-to-aft and will be susceptible to interference from cargo, lines, etc. The Z configuration can also be implemented by measuring three angles only and not measuring any distances.

"X" Configuration

The final configuration to be discussed here is the closed "X" configuration, shown in figure 5. As in the "Z" configuration, no angles need to be separately measured. Although the beam D_4 is not needed to derive the critical variables, its inclusion somewhat simplifies the mathematical processing and can be used as a redundancy for error reduction. This configuration is most susceptible to interference as two beams must pass fore-to-aft in the areas of cargo, lines, etc. The closed X configuration can also be implemented by measuring four angles and not measuring any distances.

Configuration Formulas

Figure 5 lists the formulas for each of the critical variables under each of the critical variables under each of the geometrical configurations described above. It is again noted that the formulas are for the particular configuration shown with given coordinate systems, and are therefore only one possible set from many available selections.

SENSOR TECHNOLOGIES

Active Infrared Range Sensors

The two main active infrared (IR) ranging systems in use today are the CW and pulsed types. In general, the CW ranging system operates by modulating the optical beam and then comparing the return signal generated by or reflected from the range target with the modulation signal. Pulsed ranging systems determine range by measuring the time of flight of an optical pulse from the transmitter to the target and back. CW ranging systems are usually considered to be more accurate than pulsed systems, but the pulsed systems can measure greater ranges.⁽⁶⁾ The accuracy and range capabilities of both systems, however, are sufficient for use as an UNREP range sensor.

Detection Systems for Infrared Range Sensors. Two basic types of detection systems are the incoherent detection and the coherent detection systems. In incoherent detection a photodetector collects the return beam radiation and converts it to electrical energy. Optical beam intensity is used to measure range so that beam coherence is unnecessary. Background radiation noise is normally filtered out prior to detection.

Coherent detection systems use the coherence of the optical beam mixed with a strong internal oscillator signal to produce a beat frequency that contains range information. This type of detection requires more precise beam alignment than its incoherent counterpart to ensure proper interferometric alignment of the return signal with the oscillator signal.

Active Infrared Range Measurement Accuracy Degradation Factors. Range measurement accuracy with active IR systems is affected by a complex combination of factors such as beam divergence, optics attenuation, target reflectivity, atmospheric attenuation, and noise sources. Atmospheric attenuation is due to scattering and absorption and is normally of the form $e^{-\alpha R}$ where R is range and α is the attenuation coefficient caused mainly by the affects of Mie (or aerosol) scattering.⁽⁶⁾ For a transmitter wavelength of $0.8 \mu\text{m}$, α at sea level increases from about 0.05 km^{-1} on an exceptionally clear day to 1.0 km^{-1} on a hazy day.⁽⁷⁾

Noise sources that hinder proper signal detection must be suppressed or rejected to increase the S/N (signal-to-noise ratio) above the detection threshold. Typical sources of noise are ambient background noise from spectral radiance, dark current noise from photodetector leakage, thermal noise from the postphotodetector amplification process, and quantum noise caused by noise photons under strong signal conditions.

Active Infrared Ranging System Disadvantages. An IR ranging system must overcome several disadvantages before it can be considered acceptable as an UNREP sensor system. Examples are given below.

- o The strength of the signal seen by the receiver decreases because of the exponential increase of attenuation with range and because of the radiation scattering of the transmitted beam energies by water droplets and particulate matter, especially in the visible and near infrared regions.

- o It is often advantageous to keep the divergence of transmitted electro-optical beams small since narrower beams will generally have greater accuracy and more power per unit area to be used for data transmission. However, the narrower the beam, the more difficult it becomes to acquire and track a moving target from an unstable platform, as is the case in UNREP maneuvers, and thus expensive stabilization subsystems become necessary.

- o Laser systems have the potential of being eye hazards. The potential is increased on board ship where personnel have access to and use binoculars during UNREP maneuvers. With binoculars a relatively large area beam is collected and focused down to the retinal size while retaining the power of the larger area.

- o Solar background spectral radiance presents a problem for optical frequency systems, appearing as a (noise) signal to the receiver. Most background frequencies can be eliminated using an optical filter. This does not, of course, include the frequency of the transmitted beam.

- o Cost is another disadvantage of active IR ranging systems. Of the comparably performing systems reviewed for the UNREP sensor system, active IR was always one of the more expensive alternatives. One reason for the higher cost was the high cost of the required stabilization. Also included are the trade-off costs of

providing a beam with sufficient S/N without using retrodirective units while meeting the requirements for eye safety and for signature control.

o Salt spray on the exposed optical surfaces can become a major problem by causing beam attenuation or blockage. Optics cleaning procedures, from periodic manual lens wiping to built-in air blowers, are necessary to keep the optical surfaces clear of salt spray costings.

Active Radar Frequency Range Sensors

Radar frequency range measurement systems are the most widely used type of operating system in use today. Practically every ship and airplane in the U. S. Navy employs some kind of radar acting in a search mode to detect the presence of other vehicles in the vicinity; most also employ some range measurement capability. Radar systems are usually designed to operate over much longer distances than the UNREP application. Radar frequencies are generally regarded to fall in the range 30 MHz to 30 GHz with the millimeter frequency band starting at 30 GHz. Atmospheric absorption for radar frequencies can be ignored over the ranges of interest to the UNREP application.

Radar ranging systems employ both CW and pulse transmission schemes. In both cases, ranging information is derived from the measurement of electromagnetic transit time from source to target and return.

Detection Systems. Nearly all radar receiving systems use the superheterodyne principle where the received signal is shifted to an intermediate frequency by mixing with a local oscillator.

Noise Sources. Noise sources in radar ranging systems are unwanted signals that originate both externally and internally to the system, and include signal reflections from objects other than the intended target, multipath signals, other radar system signals, receiver thermal noise, antenna noise (including "sky noise") and transmission-line thermal noise. In designing radar ranging systems for the UNREP application using low power devices, each of the noise sources must be taken into account.

Antenna Patterns. There are two ways to select antenna beam patterns for use in a range measuring system on rolling and pitching ships. The antenna beam pattern can be designed to be large enough to intersect the antennas for all conceivable ship orientations; alternately the antenna beam may be sufficiently reduced in size to require antenna rotation or even a stable platform in the extreme. Antenna patterns for radar range measuring for UNREP would most likely be wide beam systems in elevation (perhaps $\pm 30^\circ$) and omnidirectional in azimuth, to enable a passing maneuver on either side of the lead ship.

Atmospheric Attenuation. Over the ranges in question for UNREP, atmospheric attenuation is negligible for the radar frequencies below 3 GHz (a wavelength of 10 cm). Attenuation results from both absorption and scattering. Absorption can be ignored for wavelengths greater than a few centimeters.⁽⁸⁾

Attenuation by atmospheric gases arises mainly from water vapor absorption and oxygen absorption. Water vapor absorption peaks at 22,235 MHz and is directly proportional to absolute humidity, but is still low enough to be insignificant over the UNREP ship separation ranges. Oxygen absorption will be discussed in the section on millimeter wave technology.

Attenuation of radar frequency energy by dust, smog, and smoke particles are very small relative to water droplets and thus will not be discussed further in this paper.

Attenuation of radar frequency energy by rain and fog should be considered at frequencies greater than 3 GHz and generally rises as frequency increases.⁽⁸⁾ Attenuation at wavelengths of 3 and 1 cm become significant and are 0.66 and 5.5 db/km, respectively, at the heavy precipitation rate of 25 mm/hr, at 18°C.⁽⁸⁾ Attenuation in fog may get as high as a few db/km for wavelengths between 10 and 1 cm.⁽⁸⁾

Advantages and Disadvantages. An active radar range measuring system for UNREP has the following advantages:

- o Atmospheric attenuation is comparatively low. Penetration through rain, fog, dust and smoke is easy to achieve.
- o Broad beam antenna patterns are possible, allowing the design of strap-down (nonrotating) antennas.
- o Radar technology is highly developed, components are readily available and development costs are relatively low.

Disadvantages of active range measuring systems for the UNREP applications are:

- o Electromagnetic interference from other shipboard systems is potentially very high.
- o Atmospheric attenuation is too low to allow operation without increasing the ship's signature unless highly sophisticated operating schemes are used.

Active Millimeter Wave Frequency Range Sensors

Millimeter wave frequencies are generally considered to extend from 30 to 300 GHz, corresponding to wavelengths of 10 to 1 millimeters. In the frequency spectrum millimeter waves fall between the microwave and the submillimeter wave spectra (extending from 0.3 THz to 3 THz). Beyond 3 THz is the infrared spectrum.

When compared with microwave technology, millimeter wave technology has smaller components and circuitry, narrow beams are easier to generate and bandwidth is increased. Atmospheric attenuation is higher, allowing for operation without increasing the ship's signature without requiring sophisticated operating schemes.

Millimeter wave systems have a big advantage over optical systems, including infrared and visible, because attenuation due to clouds, smoke, fog, and haze is much smaller.⁽⁹⁾

Power Sources. Commonly used solid-state power sources include the IMPATT diode, the Gunn diode, and avalanche diode frequency multipliers. Solid-state devices put out low to medium power, likely sufficient for the UNREP application; higher power outputs are available from tube sources.

Atmospheric Attenuation. Millimeter wave attenuation in the atmosphere varies drastically with frequency.^{(9),(10),(11)} There are attenuation minimums at 94, 140, 220 GHz. There are attenuation maximums at 60, 118, 183, and 320 GHz. "Clear air" attenuation is largely due to atmospheric gases. The 60 GHz attenuation is about 15 db/km. Heavy rain is a comparatively large contributor to attenuation, adding another 10 db/km at 60 GHz. Fog also causes considerable attenuation but less than for infrared frequencies. Dust, smog, and smoke are not big contributors to the absorption of millimeter waves because their dielectric constants are small compared to water droplets.⁽¹⁰⁾ The attenuation due to hail and snow is also much smaller than that of rain (about two orders of magnitude) because of the difference in dielectric properties between the frozen and liquid states.⁽¹¹⁾

The 60 GHz frequency was selected as the best frequency in the millimeter spectrum at which to design an UNREP ship separation sensor. The absorption band at 60 GHz is relatively broad because there are actually several resonant lines; this keeps the 60 GHz absorption stable over time.⁽¹¹⁾

Antenna Patterns. Like microwave systems, the antenna patterns for millimeter wave devices can be designed to be broad beam or narrow beam. However, it is more difficult to generate broad beam millimeter antenna patterns because of the higher frequencies and lower power sources.

Advantages and Disadvantages. An active millimeter wave ranging system operating at 60 GHz was chosen as the candidate ship separation sensor for UNREP. It has the following advantages:

- o Atmospheric attenuation is sufficiently low to transmit over the required distance. Penetration is possible through rain, fog, and all other conceived atmospheric absorbers and scatterers.
- o Operation without increasing signature is possible because of the relatively high atmospheric attenuation values.
- o Broad beam antenna patterns are likely possible, allowing strap-down (non-rotating) antennas.
- o Background noise sources are low.
- o Electromagnetic interference from other systems is very low at the present time, but will likely be higher in the future as many other millimeter wave systems are being developed.
- o Cost is relatively low.

The primary disadvantage is that millimeter wave technology is relatively new compared with microwave technology, and thus has an associated higher risk factor for a development program.

Passive Infrared Range Sensors

Range measurement using a passive IR system can be accomplished by observing a specific part of the target's IR signature by one or more detectors. In the case where the target is a ship at sea, the detector(s) can observe one or more of the following IR sources at known locations on the ship: the stacks, the leading and trailing edges of the ship (bow and stern), bridge superstructure, and frame ribs. Range can be deduced by measuring the necessary angles between the detectors and the targets. An IR television monitor could display the ship's IR signature and the necessary measurements taken from the successive scans.

Infrared Detectors. The main component of the passive IR ranging system is the detector. The responsive elements of the detectors are radiation transducers that convert IR radiation to an electrical signal. ^{(6),(12)} The detectors are usually classified as either thermal detectors, whose elements respond to changes in temperature caused by the radiation, or photon detectors, whose elements respond to the change in the number or mobility of electrons (or holes) caused by changes in the number of IR photons. In general, photon detectors have shorter response times than thermal detectors, being of the order of 1 μ sec.⁽¹²⁾ They also don't respond to as wide a band of the spectrum as thermal detectors, resulting in a smaller limiting background noise. The disadvantage of photon detectors when compared to thermal detectors is that photon detectors generally have stricter cooling requirements,⁽¹²⁾ to ensure that the number of free carriers, caused by the incident radiation, is much greater than those excited thermally.

Range Accuracy Degradation Factors. A passive IR detection system will be subjected to many of the same range accuracy degradation factors that the active IR system experiences. Selection of a passive IR detector involves consideration of the incident IR radiation wavelength and intensity limits, the electrical output and properties of the detector, the optics, the required operating temperature, and the external bias requirements. Performance of the detector also depends on the signal modulation frequency, the spectral range to which the detector responds, and the field of view over which the background radiation is incident upon it.⁽¹²⁾

Passive Infrared Ranging System Disadvantages. The major disadvantage of a passive IR system in an UNREP ranging scenario is the lack of well-defined IR sources on the target ship. The system must be able to pinpoint the targets to enable calculation of the required parameters to within the desired accuracies.

A passive IR system also has some of the same disadvantages as an active IR system, such as solar background noise, and a decrease in IR radiation strength caused by water droplets and particulate matter in the air and potential coating of the optics caused by salt spray. However, unlike the active system, the passive system adds nothing to the ship's signature nor is stabilization of a narrow beam required.

Passive Visible Frequency Range Sensors

Passive ranging systems operating in the visible frequency range normally measure distances stadiametrically. In this method the apparent dimension of an object is related to its actual dimension through range. For example, surveyors can determine distance by means of a telescopic instrument having two horizontal lines through which the marks on a graduated rod are observed. Figure 6 shows the general stadiametric principle.

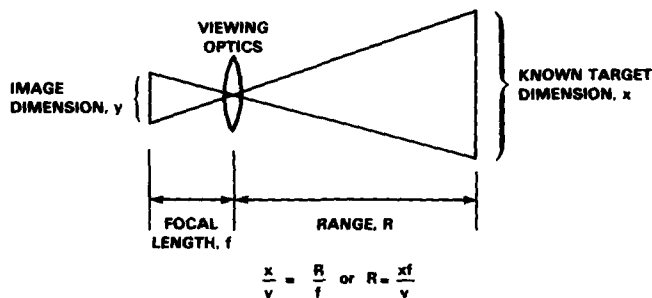


Figure 6 - General Stadiametric Principle

Detection Systems. The main difference in stadiametric passive visible ranging devices is the method used to determine the image dimension (dimension 'y' in Figure 6). Once this dimension is known, it is a simple matter of mathematics to determine range. Three possible ways to determine image height are by use of image correlation, a television system, and a photodetector system.

Two instruments in the image correlation category are the surveyors' instrument mentioned earlier and the stadimeter, which is widely used by U.S. Navy personnel to determine the approximate distance from one ship to another ship or object. The stadimeter operator makes adjustments between the direct and reflected target

images as viewed through a telescope. The stadimeter measures the angle subtended by the object (of known height) and converts it to range by means of a micrometer drum used to adjust the images. The stadimeter, however, is limited to ranges between about 200 to 10,000 yards and target heights of about 50 to 200 feet. Variations on the stadimeter correlation method are possible. For example, the target images from two mirrors a known distance apart could be reflected onto each other. When the two images coincide, the mirror angles to the target are measured. The two angles and the distance between the mirrors define a triangle from which range to the target can be determined.

In the television system method the target image height can be projected onto a television camera tube. The resulting image height on the television screen is then proportional to the actual target height, focal distance, and range. By knowing the number of television raster lines swept by the system and counting the number of lines the image covers, range to the target can be computed. Range resolution is then a function of the total number of television lines.

The target image can also be projected onto a line or array of small photo-detector diodes. Range can then be determined from the number of diodes that the image covers. Range resolution is a function of center-to-center diode spacing, which can be in the micron range.

Range Accuracy Degradation Factors. There are several factors that degrade the accuracy of visible passive electromagnetic ranging systems. These include the following:

- o Optical coatings - Like IR radiation, visible light is subject to atmospheric attenuation. The total extinction coefficient is a combination of attenuations due to absorption and scattering.

- o Background and foreground "targets" - Objects such as background open doorways or foreground UNREP rigging could offer sufficient contrast to be mistaken as targets by the detector. Similarly, an automatic tracking system could inadvertently lock on to a false target, resulting in inaccurate distance readings.

- o Contrast - The target must have sufficient contrast against the background so that the detector will be able to unambiguously define the edges. Similarly, the detector must have sufficient capabilities to be able to detect the target throughout prescribed light level and contrast conditions. The ratio of the apparent contrast of the target at some range R to the inherent contrast at zero range falls off as $e^{-\alpha R}$ where α is the atmospheric attenuation coefficient. (6), (7), (12)

- o Target size and shape - The size of the target should be chosen such that the image of the critical detectable dimension on the detector comfortably covers most of the detector area at the closest range of interest. Errors result when the target image is larger than the detector area and loss of resolution results when the image is too small. Errors due to the cosine effect will also result when a linear target dimension image is projected onto a linear detector at non-perpendicular observation angles. Proper choice of the target shape (e.g., cylindrical) can eliminate some of these problems.

- o Ambient vibration - Vibration of the detector with respect to the target will cause image jitter. If the vibration frequency is greater than the detector sampling rate, the resulting fuzziness of the image dimensions will cause errors in ranging measurements. For example, a 0.04 inch amplitude vibration will span about 68 diodes in a linear diode array on 15 μ m centers. If there are 1500 diodes in the array, 68 diodes represent a 4.5 percent uncertainty.

o TV characteristics - Nonlinearities and drift problems associated with TV camera detection methods can introduce errors in the range measurement. Also, the range resolution will be a function of the number of raster lines.

Passive Visible Ranging System Disadvantages. Passive visible ranging systems show much promise for future development. They are inherently simple and produce no emissions. The major disadvantage of the passive visible system lies in target recognition and discrimination. Weather, contrast, illumination, and atmospheric attenuation effects can combine to mask out the target from the background. Special low light level TVs are available that "see" down to the threshold of human visibility, but only at substantially increased costs.

Passive visible systems must use targets whose dimensions are considerably greater than other systems' (e.g., an IR beam) to ensure good accuracy and resolution over the UNREP ranges of interest.

False targets, such as open doorways, that present sufficient contrast to the detector, can be a problem to passive visible systems. This also applies to UNREP riggings and lines that might get in the field of view of the detector optics.

Undamped vibrations of the detector could be a serious ranging problem for passive visible systems, especially in a Navy shipboard environment. Shipboard vibrations are everpresent and can occasionally develop severe amplitudes. To overcome the induced jitter and fuzziness, a passive visible system may need vibration isolation mounts for the detector.

Active Acoustic Underwater Range Sensors

Active acoustic systems have been used for several decades to measure underwater range. Sonar systems, for example, emit signals in the water and listen, via hydrophones, to the echo, or reflected signal, from the target. Typically, the sound creates pressure variations in the water that are sensed during the echo phase by the hydrophone. As a close range ship control system, an underwater acoustic system must be capable of pinpointing the sources of the reflected signals in order to deduce the geometric position of the target ship relative to the ship which has the acoustic ranging system.

Range Accuracy Degradation Factors. There are several factors that limit the usefulness of underwater acoustic ranging systems. These can be grouped under the following headings: transmission losses, velocity variations of sound in the sea, sea surface effects, and noise sources.⁽¹²⁾

Transmission losses can be divided into losses from spreading and losses from attenuation. Spreading is a geometrical effect that causes a decrease in signal intensity at the receiver because the signal has spread outward from the source in all directions. The intensity of a signal that experiences this type of spherical spreading decreases as the square of the distance. Another type of spreading, called cylindrical spreading, can also occur when plane parallel upper and lower bounds exist on the medium. Here the intensity decreases as the first power of distance. Attenuation losses are caused by absorption and scattering. Intensity decreases by the factor $e^{-\alpha R}$ where α is the absorption coefficient and R is the range. The absorption coefficient varies as the square of frequency and is also temperature dependent.

The velocity of sound in the sea varies with temperature, salinity, and depth. Sound velocity changes approximately 5 ft/sec per degree F (near 70°F), 4 ft/sec per part per thousand (salinity), and 0.017 ft/sec per foot of depth. These effects become irregular and unpredictable in shallow waters due to the effects of surface heating and cooling, salinity changes, and currents.⁽¹³⁾ The speed of sound

in the sea is 1526 m/sec at 25° C and atmospheric pressure. This low value, compared to the speed of electromagnetic wave propagation, can impose time update problems for range measuring systems.

The water-air interface acts as a reflecting surface to underwater acoustic signals. Losses at the sea surface are a function of sea roughness, angle of incidence, and signal wavelength. Of theoretical interest is the Lloyd mirror or image interference effect where the intensity at a point is altered by the constructive and destructive interference of the source signal and the surface reflected signal. However, at kilohertz frequencies the rough sea surface usually obscures these effects.⁽¹³⁾ Of more importance are the shadow zones created when a negative gradient exists below the sea surface. For shallow sources, the surface casts a shadow in which the intensity of the signal is greatly reduced. (A sea bottom shadow zone can also exist.)

There are several sources of ambient pressure changes in the ocean, both acoustic and non-acoustic, to which pressure-sensitive detectors will respond. Many of these sources, such as tides and seismic disturbances, produce pressure changes that lie well below the range of interest in underwater acoustic range measuring systems. Other low frequency noise generators are the hydrostatic effects of waves, oceanic turbulence, biological sounds, distant ship traffic, and storms. Ambient sea states and wind conditions as well as rainfall, contribute to the background noise particularly in the 500 Hz to 25 kHz region.⁽¹³⁾ Finally, there is the thermal noise of the sea molecules which puts a theoretical limit on the high frequency hydrophone sensitivity.

Active Acoustic Underwater Range System Disadvantages. Major disadvantages of using an underwater acoustic system for a close range ship control ranging system are those related to subsurface mounting of the sensors and time update problems. Hull penetrations are required and accessibility is a problem. Update times of once per second are required for extreme weather conditions for close range ship control are not possible for ranges beyond 763 meters (or less if the sensing technique requires any averaging). Sound velocity variations, particularly due to temperature and salinity variations, are sources of error that must be addressed in the ocean environment. Also, there will be some doppler effects generated by the fact that the ships are moving relative to each other (including roll, pitch, etc.) and that ocean currents and turbulences exist.

Active Acoustic Airborne Range Sensors

A general airborne acoustic system is similar to an underwater acoustic system, both consisting of an acoustic signal generator and a receiver to sense the acoustic return signal reflected off the target. The airborne acoustic system must also be capable of pinpointing the locations of the reflections to be useful as a close range ship control system. The velocity of the airborne signal is also affected by temperature and pressure and is susceptible to variations caused by the doppler effect. But an airborne acoustic system has one major drawback that prohibits its use as a close range ship control ranging system. The velocity of sound in air is approximately 1090 ft/sec so that an acoustic signal would travel for about 1.8 sec at a 1000 ft separation (2000 ft round trip). The close range ship control system requires that the range information be updated at intervals of 1.0 sec or less. The airborne acoustic system is therefore limited to a maximum range of about 550 ft, which is prohibitively small. Further discussion of airborne acoustic systems will therefore not be given.

SUMMARY COMPARISON

The distance-measuring systems described above are based on several technologies that have possible application to the David Taylor Naval Ship R&D Center

Close Range Ship Control (UNREP) program. Selection of a system to be used as the UNREP sensor involves weighing their advantages against their disadvantages in an at-sea environment under the proposed configuration, identifying high-risk areas, projecting future development, and comparing system costs. The advantages and disadvantages of each of the instrument techniques were discussed. It is now necessary to bring them together in summary to facilitate comparison of each system's strong and weak points relative to the UNREP sensor system specifications. Advantages and disadvantages of the various configurations noted in the Sensor Configurations section will be examined first. Then the advantages and disadvantages of various sensor technologies experienced in the sensor selection part of the UNREP program will be discussed.

Summary Comparison of Configurations.

Table IV lists advantages and disadvantages of the various configurations that were examined during the UNREP program. In general, the more complex the configuration, the more independent the system becomes in obtaining the required control parameters. It is also possible with the more complex configurations to determine the effects of ship motions (roll, pitch, etc.) by positioning the sensor units in offset locations, i.e., not all in a single plane parallel to the water surface and not all equidistant from the ship centerline. The mathematics, of course, also become more complicated and the cost increases with complexity.

The closed X configuration was chosen for the UNREP sensor development, mainly because of the advantages listed in Table IV. One or more of the other configurations may be used during the development cycle, but the closed X configuration offers more for a final system.

Summary Comparison of Specific Instrument Technologies

Table V summarizes the characteristic advantages and disadvantages of several different specific instrumentation technologies that were reviewed during the sensor selection phase of the UNREP program. The methods and alignments noted in the table apply to the particular system that was reviewed and is not meant to be the only method and alignment available to the entire technology. All systems, however, have to overcome certain ambient environmental factors that degrade the performance to ensure sufficient signal-to-noise ratio while neither increasing the signature of the ship nor sacrificing safety. Rain appears as a direct factor affecting system performance to varying degrees in all technologies except underwater acoustic. However, depending upon rainfall rate, system response, etc., even an underwater acoustic system can be susceptible to performance degradation due to rain because of the acoustic noise generated upon impact of the rain with the sea surface.

The attenuation effects of rain, fog, and atmospheric absorption noted in Table 5 are shown in Figure 7. Fog and the heavier rains are major contributors to attenuation throughout the spectrum shown, with attenuation due to fog increasing beyond the millimeter range. The attenuation at constant rainfall remains relatively constant from the far infrared through the visible. The fine structure of the atmospheric absorption curve between about 700 GHz and 10 THz is of little importance to this study, because components are not readily available, and is therefore not given.

CONCLUSIONS

The measurement of close range ship separation distances and relative orientation can be accomplished with several different technologies and design configurations. Technologies considered included both active and passive, electromagnetic and acoustic sensors, across a wide frequency spectrum including, microwave

Table IV. Advantages and Disadvantages of the Various Configurations

Config- uration	Advantages	Disadvantages
"I"	<ol style="list-style-type: none"> 1. Less costly, only two units. 2. Lowest chance of beam interference. 	<ol style="list-style-type: none"> 1. Need lead ship and approach ship angle information.
"V"	<ol style="list-style-type: none"> 1. Low cost, only three units. 	<ol style="list-style-type: none"> 1. Need bearing angle information.
"II"	<ol style="list-style-type: none"> 1. Medium Cost 2. Low chance of beam interference 	<ol style="list-style-type: none"> 1. Need one angle measurement.
"Z"	<ol style="list-style-type: none"> 1. Can determine all parameters by distance-only, angle-only, or combination measurements 	<ol style="list-style-type: none"> 1. Requires four sensors. 2. Higher beam interference probability.
"X"	<ol style="list-style-type: none"> 1. Can determine all parameters by distance-only, angle-only, or combination measurements. 2. Has redundant measurement. 	<ol style="list-style-type: none"> 1. Requires four sensors. 2. Highest beam interference probability.

Table V. Summary Comparison of Specific Ship Separation Sensor Designs

Technology	Method	Alignment	Signal Attenuation	Environmental Factors Causing Degradation	Comments
Millimeter	Transit Time	Automatic-wide beam	15 dB/km (at 60 GHz)	Rain, moderate to heavy (2 to 10 dB/km)	1. Small components 2. Low background signals 3. Technology not fully developed
Acoustic (Underwater)	Transit Time	Automatic-Omnidirectional	100 dB/km (at 325 kHz)	Water temperature, salinity, currents, depth, ambient noise (pressure) variations	1. Underwater mounting/maintenance problems 2. Slow update 3. Shadow zones
Visible	Stadia-metrics	Manual	No emissions	Sea spray, rain, ice on optics	1. Large and complex targets with contrast necessary 2. False targets possible 3. High system cost 4. Vibration problems 5. Based on simple, proven principle
Infrared Laser	Transit Time	Manual-Narrow beam	.03 dB/km (.904 μ m)	Solar radiation, rain and fog (5 to 200 dB/km)	1. Low S/N 2. High cost 3. Needs alignment control 4. Proven distance measurement techniques
Infrared Lasing Diode	Transit Time	Manual-Wide beam	.03 dB/km (.93 and .80 μ m)	Solar radiation, rain and fog (5 to 200 dB/km)	1. Low S/N 2. Safety hazard 3. High cost 4. Proven distance measurement techniques
Radar	Transit Time	Manual-Wide beam	<.01 dB/km	Rain (excessive) (above 3 GHz)	1. Low S/N 2. EMI problems 3. Well-developed technology 4. Readily available components 5. Need alignment control
Radar	Induced Doppler	Automatic-Omnidirectional	<.01 dB/km	Rain (excessive) (above 3 GHz)	1. Low S/N 2. All parameters derived from angles only 3. Well-developed technology

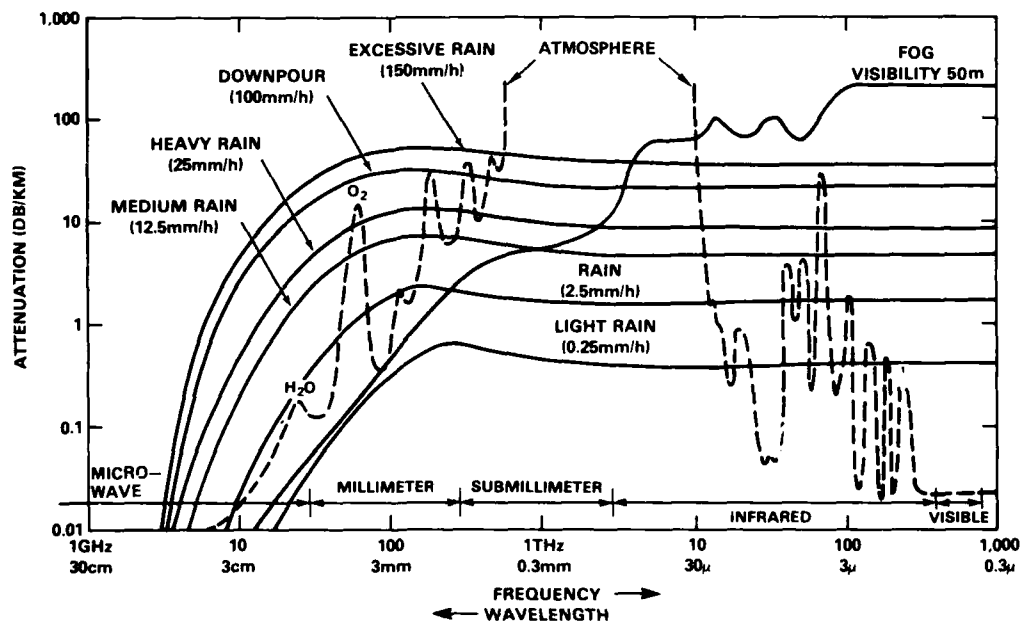


Figure 7* - Attenuation by atmospheric gases, rain and fog

*Adapted from Priessner,¹¹ Burrows and Attwood,¹⁴ and Radio Corp. of America¹⁵

millimeter wave, infrared and visible. Electromagnetic sensors were chosen for the UNREP application because of the comparatively fast update times.

Millimeter wave technology was chosen as the best UNREP range sensor development approach because of the possibility of achieving required accuracies, using broad beam (non-rotating) antennas, and not increasing the ship's signature.

Infrared distance measuring sensors are a strong second choice for the UNREP application because of their inherent high accuracy. Their major drawback is the use of narrow beams, requiring precise alignment control.

Passive visible or infrared distance sensors are strong candidates for ship-board applications because they do not increase ships' signatures. The technology is not as well developed and would likely be more expensive.

Radar frequency distance sensors have the advantage of a highly developed technology but require very sophisticated systems to ensure that the ship's signature is not increased.

Several design configurations are possible to measure two-dimensional separation distance, relative heading and their rates for the UNREP application. The I and Z configurations appear to be the simplest to instrument.

FUTURE PLANS

The close range ship control sensor for UNREP is presently being developed based on millimeter wave technology. A model will be evaluated at sea onboard Navy ships. The sensor design will then be refined and an advanced development model will be designed, fabricated, and evaluated.

The approach ship controller algorithms have been designed and will be evaluated in a hybrid computer simulation at the David Taylor Naval Ship R&D Center. Future plans include evaluating the controller hardware onboard a Navy ship and refining the design in an advanced development model. The controller hardware package will include a display on the bridge wing and provisions for manual, display-aided manual, and automatic ship control. The system will be capable of operating during all phases of UNREP including approach, station-keeping, and breakaway.

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MICROCOMPUTER SYSTEMS FOR GAS TURBINE CONTROLS

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ABSTRACT

The paper describes part of the development of a microprocessor based system for the control of industrial or marine gas turbines. It specifically evaluates the performance of 8 bit processors as the controlling element. The following factors are discussed:

- (a) The use of digital algorithms (including the effects due to variations in sampling rates and quantisation).
- (b) Hardware-software tradeoffs in the system implementation.
- (c) Processor utilisation and store requirements.
- (d) Software design techniques using both assembler and a high level language (Coral 66).
- (e) The use of structured programming in conjunction with Coral 66.

INTRODUCTION

At the present time the great majority of Gas Turbine electronic control systems are still analogue, not digital. However it is believed that the use of a digital (processor based) control system may lead to an improved performance of the Gas Turbine unit, either in the industrial or marine fields. The improvements lie in a number of areas, but all are aimed at getting a better performance with enhanced fuel economy. How can this be achieved?

Firstly, by operating the Gas Turbine closer to its operating limits (safely), existing designs can be uprated.

Secondly, by adapting the control parameters over the engine running range, a number of benefits are obtained. Both the stability and the required transient responses can be maintained at nearly all points in the power range. This should lead to improvements in both performance and consumption when compared with analogue control systems.

A third major area is the use of trend and health monitoring systems. These are much easier to implement when using digital control systems. However, these digital techniques have not made it actually any easier to measure the engine parameters. Therefore some of the engine manufacturers may be forgiven for having a slightly jaundiced view of this subject.

This paper describes the initial assessment of the performance of a microprocessor based control system for a typical twin spool industrial/marine Gas Turbine. The control technique is ready for evaluation on a Gas Turbine Simulator but unfortunately completion of this part of the programme has been delayed by non availability problems with the simulator.

THE PROBLEM

Before digital control techniques and systems are evaluated, and words such as "optimal", "adaptive", etc. appear it is instructive to examine the basic problem.

The control of power and/or speed of the Gas Turbine is achieved by controlling the fuel supply (fig.1). The Control Scheme described here is shown in fig.2, where the primary controlled parameter is the shaft speed of the gas generator (N_1). However this loop must also take into account the performance envelope limits (fig.3) set by the compressor delivery pressure (P_3), power turbine shaft speed (N_2), and exhaust gas temperature (T_6). It is also subject to limits on the gas generator shaft speed (N_1). Furthermore, the rate of change of fuel flow must be limited to stop overfueLLing during acceleration (avoiding compressor surge) and underfueLLing during deceleration (preventing flame extinction) as shown in fig.4. These factors define the control system task.

The problem is made much more difficult because the dynamics of the engine are a function of its speed. Therefore any fixed control strategy must be a compromise to allow for all running conditions. This is one of the main limitations of present day analogue systems.

WHICH CONTROL TECHNIQUE/STRATEGY?

Performance improvements can only be obtained with an adaptive control system, which can be achieved fairly easily with a processor based equipment. However this doesn't answer the big question, which is "what control strategy?". The ultimate in control techniques would be to incorporate an adaptive self-tuning controller using optimal control strategies. Unfortunately a number of new problems are raised by going down this particular path. One major factor for the engine manufacturer is the degree of technical support needed for the system. Conventional linear (and non-linear) control methods are well understood by the gas turbine engineer, but a much higher academic level is needed to cope with modern control theory. Therefore the engine manufacturer not only has the problem of introducing a new technology (digital electronics) but also now needs very high calibre engineers in these new disciplines to support his system.

Very much for this reason it was decided to evaluate an alternative approach, which will here be called "sub-optimal". Generally the Gas Turbine System can be accurately described mathematically by a transfer function whose coefficients are a function of the engine operating condition. At any point in the range a conventional type of control scheme will give a perfectly acceptable response. However the "tuning terms" of the controller must be varied over the engine speed/power range to maintain this performance.

The sub-optimal control method breaks up the full range of the Gas Turbine into a number of operating regions. The unit is described by a specific linear transfer function for each region, and corresponding tuning terms are implemented by the Controller for these regions. Thus the control strategy is "adapted" to suit the engine operating conditions, but in a known defined manner.

THE CONTROL SYSTEM

The control system which is to be implemented digitally is based on existing control techniques (fig.5). In general the system runs in speed control (N_1). Here the error between the desired and actual speeds sets up the fuel demand signal. An inner (minor) control loop controls fuel flow in response to this signal. The fuel demand signal can be reduced at a "least wins" gate by the other control parameters. This allows the fuel demand to be backed off as limiting conditions are approached. A further input can increase fuel flow at the "most wins" gate to ensure that flame extinction doesn't take place under deceleration

conditions. The work described here is concerned with the way in which the controller was realised using a microcomputer system. A twin shaft design of engine is considered which has the following transfer function for small perturbations about any running point x :

$$P_3 = K_3 \left[\frac{1 + S(aT_e)}{(1+ST_e)(1+ST_c)} \right] \dot{f} \quad (1)$$

$$N_1 = K_1 \left[\frac{1}{(1+ST_e)(1+ST_c)} \right] \dot{f} \quad (2)$$

$$T_6 = K_6 \left[\frac{1 + S(bT_e)}{(1+ST_e)(1+ST_c)(1+ST_d)} \right] \dot{f} \quad (3)$$

$$\text{where } K_3 = \frac{\delta P_3}{\delta F \cdot x} \quad K_1 = \frac{\delta N_1}{\delta F \cdot x} \quad K_6 = \frac{\delta T_6}{\delta F \cdot x}$$

and T_e = Engine inertia time constant
 T_c = Combustion time constant
 T_d = Exhaust duct time constant

THE CONTROL TRANSFER FUNCTION

It was known from experience that quite acceptable results could be obtained without putting signal processing in the feedback path. Thus it was decided initially to implement a control algorithm in the forward path based on a lead/lag compensation of the form.

$$\left[\frac{K \frac{1 + ST_1}{1 + ST_2}}{\frac{1}{A}} \right] \left[\frac{1 + ST/2_B}{1 + ST_2} \right]$$

The first problem is to produce this transfer function in the digital controller. What many people do not realise is that any digital algorithm, whether it be Z-transform, Poisson Summation Rule, difference equation, etc., is only an approximation to the original continuous algorithm. This approximation can in itself lead to unexpected problems in closed loop digital control systems. Thus we need a transform which makes both the continuous and the discrete algorithm alike as possible.

The method used here is one which makes use of a Taylor's Series expansion of the sampled inputs. For detailed information on this technique the work described in refs. 1, 2, 3 should be consulted.

At this point we can now define the main items for investigation and analysis.

MICROPROCESSOR SOLUTION - THE PROBLEMS

The problems which arise from the use of a microprocessor can be grouped as follows:

- (a) Those related to the choice of control algorithm
- (b) Software design and documentation
- (c) Operator interaction with the processor

Note that the work in the following sections relates to the type of control system shown in fig. 6.

THE CONTROL ALGORITHM

Speed

It will be seen later that the processor spends most of its time computing the required control signals. Relatively little time is taken to either acquire or to output signals. It takes a finite time to compute the fuel control signal, and the update rate of this signal is dictated by the plant dynamics. A suggested figure is approximately 80 times per second, or 13mSecs. between updates. A complex control algorithm places a greater time penalty on the processor than a simpler one.

Algorithm Errors

When an output signal is computed there will normally be an error present (when compared with the continuous algorithm computations). This is due to two factors; firstly the algorithm truncation error, and secondly, the signal quantisation error. The first error occurs because the digital algorithm is an approximation to the continuous one. Its significance depends on the particular algorithm chosen. The second error arises from the finite digital word length of the analogue to digital converter and of the computer itself.

Choice of Sampling Rate and Quantisation Level

It would appear at first sight that fast sampling rates are desirable. Initially this indeed does reduce the total error, specifically the truncation error (ref.4). Unfortunately the quantisation errors increase as the sampling rate increases. Therefore the total error reaches a minimum and then begins to rise as the sampling rate increases. An error plot for a particular algorithm is shown in fig. 7 (ref. 4). Therefore for each algorithm there is an optimum sampling rate h_0 which is a function of the system quantisation.

When digital algorithms are used in closed loop control systems the errors discussed here can lead to problems in both steady state accuracy and system stability. Experience to date has indicated that best results are obtained by sampling at between four and ten times the system bandwidth.

Processor Performance

One of the main concepts behind this work is in the use of distributed control schemes. Microprocessors (and associated components) are so inexpensive that they can be dedicated to specific tasks rather than being shared amongst a number of jobs. This is particularly true of the more recent 8 bit machines which have been clearly aimed at tasks such as control systems. Therefore this work has concentrated on the 8 bit microprocessor. Unfortunately the control algorithms are going to need greater precision than 8 bits, and will also involve multiplication (and possibly division). Thus multi-word length working is the order of the day, and this imposes a considerable speed overhead on 8 bit systems.

SYSTEM PERFORMANCE EVALUATION - 1

The first part of the evaluation programme (ref. 5) was concerned with the development of the control algorithms on an 8085 processor. All functions were performed on software and the programmes were written in Assembler language. The algorithms representing the system shown in Fig. 8 were then tested using step, ramp, and acceleration functions. Some typical results are shown in fig. 9. The overall processor and store requirements were assessed as follows:

(a) Time

FUEL CONTROL SYSTEM FUNCTION	PROCESSING TIME (mSecs)	NUMBER IN SYSTEM	TOTAL TIME (mSecs)
Three Term Controller	6.9	5	34.50
Summing Junctions	0.19	5	0.95
Look-up Tables	0.085	4	0.34
Lowest/Highest Wins Gate	0.29	2	0.58
			36.37mSecs

(b) Storage

ITEM	NUMBER OF STORE LOCATIONS (BYTES)	
	RAM	PROM
Microprocessor Working Store	64	-
Three Term Controller Programme	140	715
Lowest/Highest Wins Gate	-	104
Summing Junctions	-	83
Look up table programme	-	535
	204	1437

These results showed clearly that there was no chance of meeting the performance requirements by using software techniques only. A breakdown of the processing time showed that over 19mSecs were spent on multiplications for the control algorithms. And this had been limited to 8 x 16 bit operation! It is clear that the basic 8 bit processor has to be enhanced with a hardware multiplier. To ensure that further work on the 8 bit system was worthwhile an assessment was made of the use of a TRW fast 8 x 8 bit hardware multiplier in the system. The results showed that the system processing time could be reduced to 15mSec.

SYSTEM PERFORMANCE EVALUATION - 2

Development Unit

The second part of the system development and evaluation (ref.4) involved the use of actual hardware. The microcomputer system used was not specifically designed for Gas Turbine systems but was a standard industrial equipment. The hardware configuration is shown in fig. 10 and comprised:

- (a) An Intel based CPU module with hardware timers, serial I/o channel, and a multi-level interrupt structure (DCE-X).
- (b) A memory module holding 8KBYTE EPROM and 4KBYTE RAM (MX-84).
- (c) A high speed maths module capable of carrying out a variety of mathematical functions (HSM).
- (d) An 8/16 channel fast 12 bit analogue input module (RWC-V8/16).
- (e) A two channel analogue output module (RWC-A02).

The system also included an EPROM programming module which was used to make on-site alteration during development work.

Software support for programme development on the actual equipment was provided by a 2KByte Utility package. This provided Terminal input/output control, display

and modification of memory and register contents, programme trace and step facilities, programming of EPROMS and paper tape control.

Software Development

All of the software development was carried out in assembly language using a cross assembler on a Prime mainframe computer. The development package included a simulation facility to enable programmes to be tested with simulated inputs.

The highest level of the programme is shown in fig. 11, and should be read in conjunction with fig. 5. The programmes were developed as sets of segments which were joined together to form the complete programme. An example is given in fig.12, with the corresponding assembler in fig.13. The programmes rely heavily on segmentation and sub-routines.

Changes were made to the detail of the control scheme, for instance by developing lead/lag compensation techniques and by using 16 x 16 bit multiplication. The resulting performance figures and resource were as follows:-

(a) Time - Total Control Programme.

FUNCTION	NUMBER OF CLOCK STATES		EXECUTION TIME WITH 2 MHz CLOCK	
	PROCESSOR	MATHS MODULE	PROCESSOR	MATHS MODULE
READ IN 6 NEW INPUTS	3600	-	1.80mS	-
POWER-SPEED SCHEDULE	1900	300	0.95mS	0.15mS
NEW ERROR VALUES	1100	100	0.55mS	0.05mS
N ₁ CONTROL ALGORITHM	6260	1000	3.13mS	0.50mS
N _p CONTROL ALGORITHM	6260	1000	3.13mS	0.50mS
T ₆ CONTROL ALGORITHM	6260	1000	3.13mS	0.50mS
P ₃ CONTROL ALGORITHM	6260	1000	3.13mS	0.50mS
ACCELERATION SCHEDULE	1900	300	0.95mS	0.15mS
LEAST WINS GATE	1100	100	0.55mS	0.05mS
DECELERATION SCHEDULE	1900	300	0.95mS	0.15mS
MOST WINS GATE	500	40	0.25mS	0.02mS
PREDICTED F _B	6260	1000	3.13mS	0.50mS
PREDICTED F _E	200	20	0.10mS	0.01mS
F CONTROL ALGORITHM	6260	1000	3.13mS	0.50mS
TIMOUT FUNCTION	100	-	0.05mS	-
WRITE OUT NEW OUTPUT	500	-	0.25mS	-
TOTALS	50360	7160	25.18mS	3.58mS
	57520		28.76mS	

(b) Time - Control Algorithm Execution.

FUNCTION	NUMBER OF CLOCK STATES		EXECUTION TIME WITH 2 MHz CLOCK	
	PROCESSOR	MATHS MODULE	PROCESSOR	MATHS MODULE
ALGORITHM COEFFICIENTS AND PREVIOUS OUTPUTS AND INPUTS MOVED TO RAM UPDATE PREVIOUS ERROR VALUES	1420	-	0.71mS	-
HARDWARE MULTIPLY	2460	980	1.32mS	0.49mS
HARDWARE ADDITION	1160	20	0.58mS	0.01mS
ALGORITHM OUTPUT ROUNDED TO 12-BIT NUMBER	180	-	0.09mS	-
PREVIOUS ALGORITHM OUTPUTS UPDATED, AND CHANNEL INFORMATION MOVED BACK TO STORES AREA	860	-	0.43mS	-
	6260	1000	3.13mS	0.50mS
	7260		3.63mS	

(c) Comparison with earlier System (Salient Points).

FUNCTION	FIRST EVALUATION		CURRENT EVALUATION	
	PROGRAM STORAGE	TIME (WITH 2 MHz CLOCK)	PROGRAM STORAGE	TIME (WITH 2 MHz CLOCK)
LFAST GATE ROUTINE	104 BYTES	0.43 m Sec	70 BYTES	0.60 m Sec
MOST GATE ROUTINE	104 BYTES	0.43 m Sec	70 BYTES	0.27 m Sec
EACH SUMMING JUNCTION	83 BYTES	0.29 m Sec	37 BYTES	0.15 m Sec
EACH SCHEDULE	(157 BYTES)	0.12 m Sec	(138 BYTES)	1.10 m Sec
ALGORITHM FUNCTION	690 BYTES	10.35 m Sec	195 BYTES	3.63 m Sec
TOTAL PROGRAMME		36.37 m Sec		28.76 m Sec

Comments

The results obtained show that the system as it stands is still too slow. However if the 2MHz 8080 is replaced by a 4MHz. Z80 processor (or a 5MHz. 8085) then the required update rate is met. Some other points of note are as follows:

- (a) Use of the maths module: this affected the speed of operation, store requirements, programming technique and programme development.
- (b) Speed of operation: the speed improvement is entirely due to the use of the hardware maths module. Further speed improvements (in the order of 3mSec) could have been achieved by using look-up table techniques of computing several schedules.
- (c) Store requirements: The reduction in the amount of PROM space needed is not significant but could have been further reduced if so required. This is not a problem area at all.
- (d) Programme Development and Technique: The use of the maths module very considerably simplified the software for generating the control algorithms. Also this module allowed other functions to be more easily implemented (i.e. the summing junctions).

SOFTWARE DESIGN AND RELIABILITY

Introduction

Programmes developed in assembler language usually produce the most compact and efficient microprocessor machine code. Unfortunately they have a number of drawbacks, such as:

- (a) Each microprocessor has a different assembler language. This causes problems when trying to use a mix of micros.
- (b) The design effort is very high when compared with say Basic, Fortran, etc.
- (c) The designer usually needs a detailed understanding of the micro if the resulting code is going to be compact and efficient.
- (d) Even with good documentation it can be very (nay, amazingly) difficult to understand the design. This also applies to the original designer if he has a break of just a few months from the job.
- (e) Debugging and modification of the programmes by personnel other than the original designer is a horrendous task.
- (f) The chances of the software running correctly on another system is very close to zero.

So what are we going to do about it? These problems were met and evaluated years ago in the Data Processing field. From their experience the concepts and techniques for good programme design were defined, and these have been applied to the Gas Turbine control problem.

Design Objectives

We want to end up with software which is:

- (a) Reliable : It shouldn't have mistakes or produce errors when operating (i.e. get it right in the first place).
- (b) Maintainable : Make it easy to put in modifications/changes.
- (c) Stable : When a change is made to part of a programme there should be minimal effects on the rest of the programme.
- (d) Portable : Make the software so that it will run on other computers systems.

- (e) Robust : It should continue running even though some specification has been violated (i.e. out of limit parameter) and furthermore recognise the problem.
- (f) Understandable : It should have a low complexity so that it is easy to see what is happening (or is supposed to happen).
- (g) Well Documented : The documentation must be clear and precise if the software is expected to have a long life.

Are these ideas too high-flown to be achieved in practice? Well, nobody is perfect, but the techniques described below can produce immense improvements in the quality of software. From the results obtained here it has been possible to evaluate many of these factors. These include such items as software design effort, software reliability, processor speed/utilisation, and store requirements.

Software Design

- (a) Use Top Down programming: This technique says that the problem should be tackled by first defining the problem at its simplest (top) level. This is then expanded on at the next level down, and the process is continued until the point is reached at which the programme can be produced. The structure is shown in fig. 14 and a specific example from the Gas Turbine system in fig. 15.

The beauty of the "Tree" diagram is that the whole process is visible whilst the detail is also shown. In contrast the flow chart buries the reader with detail.
- (b) Use Structured Programming: This is based on an engineering solution to the writing of programmes. The approach is planned, systematic, and defined. The control structures allowed are shown in fig. 16, where the main feature is that only one input and one output are allowed. This increases programme reliability.
- (c) Use Modularisation: Make it simple and small! Split the programme into manageable chunks. It then becomes much easier to test, debug, and modify the resulting software. It also increases the stability of the system. An example is shown in fig. 17, which can also be related to the design example of fig. 15.
- (d) Use a High Level Language (HLL): It is much easier to see what is happening when a high level language is used (fig. 17). This leads automatically to programmes which have a good chance of running correctly. However the right type of language must be chosen so that it fits in with the other concepts of programme design. Look for a "structured" language.
- (e) Produce good documentation: This is just good, sensible standard engineering practice. Like any branch of engineering the details and formats of the documents vary. However the minimum needed for good design are as follows:
 - (i) System diagram (i.e. fig. 7), input/output parameters, performance specifications, etc.
 - (ii) Structured Design (Tree) diagram (fig. 15).
 - (iii) Programme (fig. 17).
 - (iv) Test procedures.
 - (v) Use of computer resources (i.e. processor spare time, spare memory, etc).
 - (vi) Modification listing.

COMPARISON OF DESIGN TECHNIQUES

The answers given here can only be used as a broad guide for two reasons. Firstly, no two designers are going to produce the same result. A lot depends on the man actually doing the work. Secondly, the efficiency of the compiler for the

high level language will vary from system to system. Nevertheless the following points will generally be found to be true:

- (a) Design effort: This is the "how long is a piece of string" question. However, use of an HLL and a structured design method significantly reduce the design effort. The reduction is somewhere of the order of a factor of 5 to 10 when compared with the assembled version.
- (b) Understandable: The HLL version is much clearer and can even be followed by software engineers not familiar with Coral 66. Fewer diagrams are produced (one tree chart compared with 12 flow charts in the assembler version) and far fewer lines of printout are obtained (221 lines for Coral compared with 872 for the assembled version).
- (c) Reliable, Maintainable: Both of these are directly influenced by the ability to understand exactly what is happening. It is impossible to put numbers on this except to say that with the HLL it became a whole new ball game, with us on the winning team.
- (d) Portable: No present day HLL can be truly portable. In the end the hardware configuration of real time control systems affects the software. However by placing the software addressess of all input/output signals in the micro memory structure ("memory mapping") then a higher level of portability is achieved. It would also help if all compilers of the same type (i.e. Coral) actually were the same.

The portability of an assembled programme is limited (to put it mildly). The programmes can only truly be run without change on the same hardware configuration. And a change of processor type (unless it is code compatible) is just not on.

- (e) Performance: In life, unfortunately, you never get something for nothing. HLL's degrade the performance because we no longer have an optimum design. However an interesting point arose from the work described here. The assembled version made wide use of subroutines in order to reduce the design effort and to produce a more reliable system. This technique reduces the storage needs but increases the execution time. Thus a comparison of results (below) shows that the execution time of the compiled programme is only slightly greater than the assembled version.

CONTROL PROGRAMME PERFORMANCE			
	ASSEMBLED	COMPILED	% CHANGE
BYTES OF STORAGE (PROM)	1250	1827	+46%
BYTES OF STORAGE (RAM)	176	111	-59%
OVERALL TIME (mSecs)	28.76	29.12	+1.25%

Further details can be found in ref. 6.

CONCLUSION

The results presented here have shown that some current 8 bit microprocessors are capable of carrying out the control task on a Gas Turbine unit provided they are enhanced with a fast hardware multiply/divide function. This is true even when the programmes are developed using structured programming techniques and are written in a High Level Language (Coral 66). The store requirements are minimal. Therefore it is economical to dedicate a single processor to the specific task of carrying out the closed loop control of the Gas Turbine. If however the control task is extended for any reason then this paper indicates that the increased performance of a 16 bit microprocessor should be considered.

The use of structured programming together with a high level language produced a software design which had many desirable features. It was much easier to produce, was quite easy to understand, and as such, is much more reliable, maintainable and portable (when compared with the assembly language version). The performance penalties incurred were acceptable in this application.

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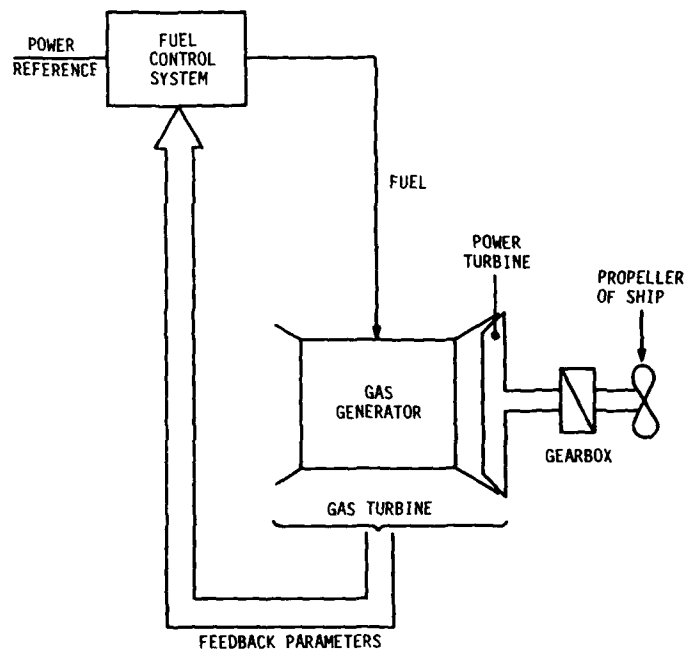
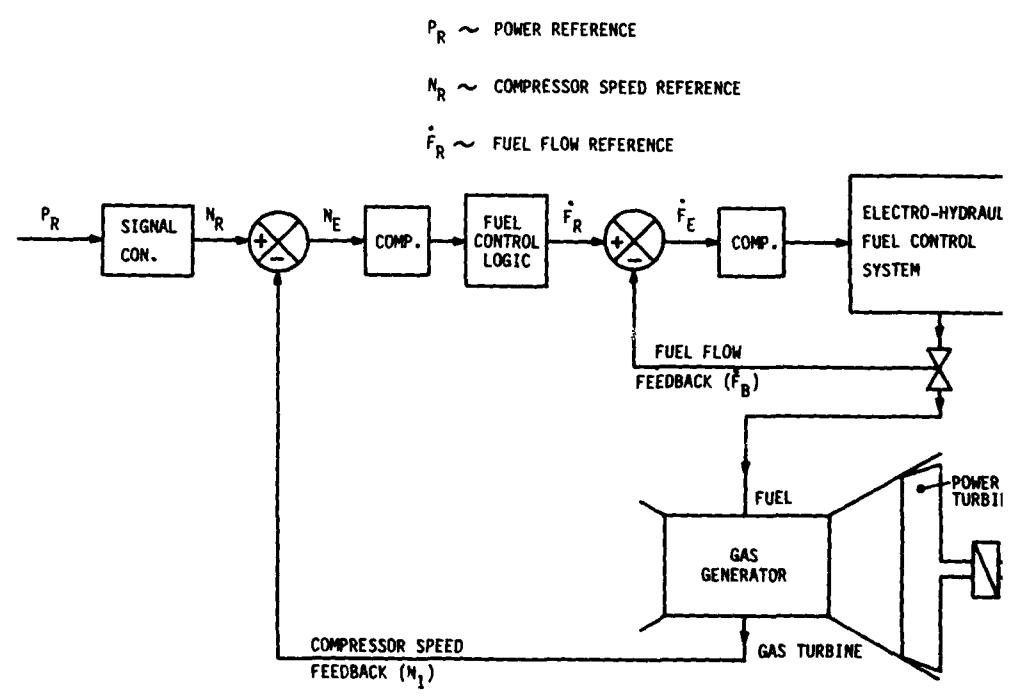


FIG 1 BASIC FUEL CONTROL LOOP FOR MARINE GAS TURBINE INSTALLATION
P2 1-13

FIG 2 FULL-RANGE POWER LOOP AND INNER FUEL FLOW LOOP



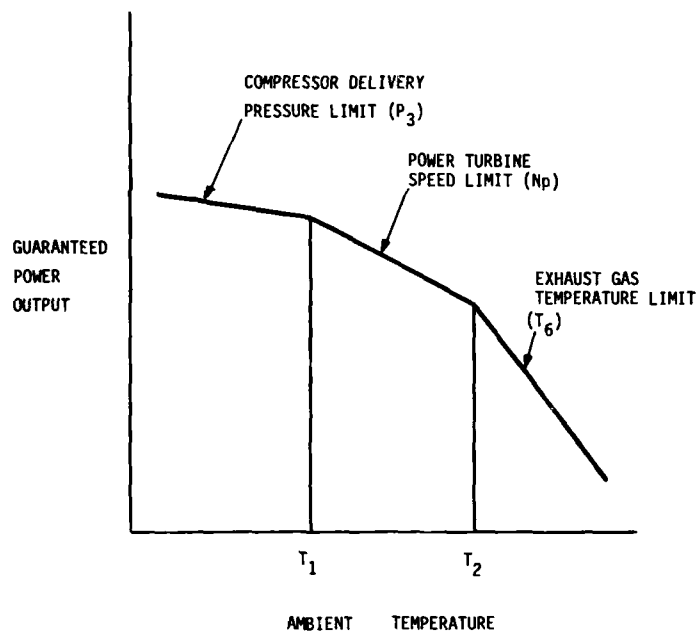


FIG. 3 TYPICAL GUARANTEED PERFORMANCE ENVELOPE

112 3-16

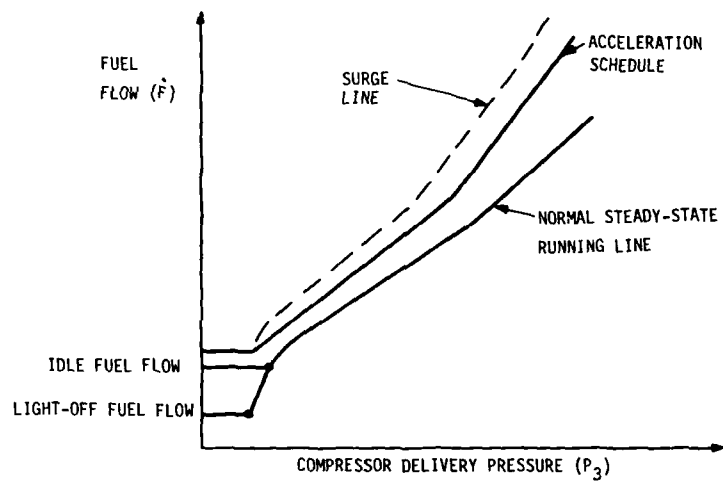


FIG. 4(a) TYPICAL ACCELERATION SCHEDULE

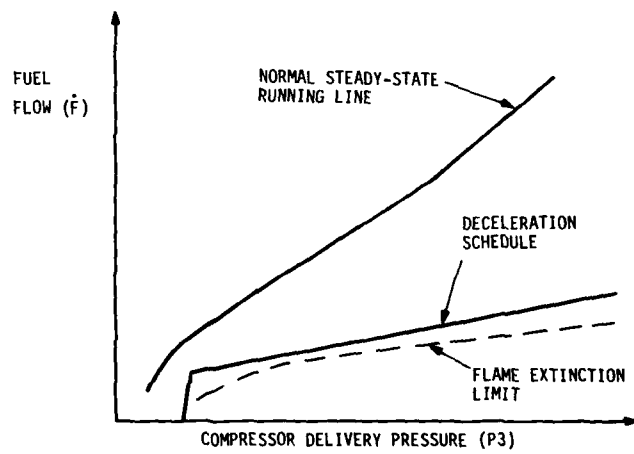
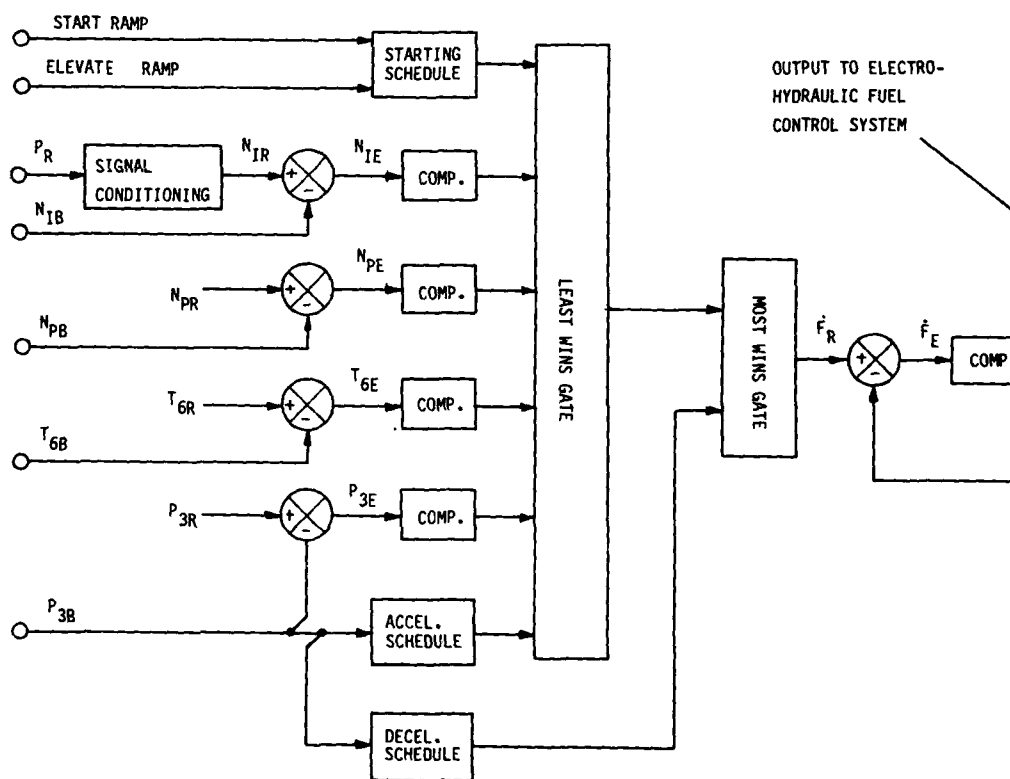


FIG. 4(b) TYPICAL DECELERATION SCHEDULE

FIG. 5 BASIC CONTROL SCHEME FOR A TWIN-SHAFT
MARINE GAS TURBINE
E2 3-17



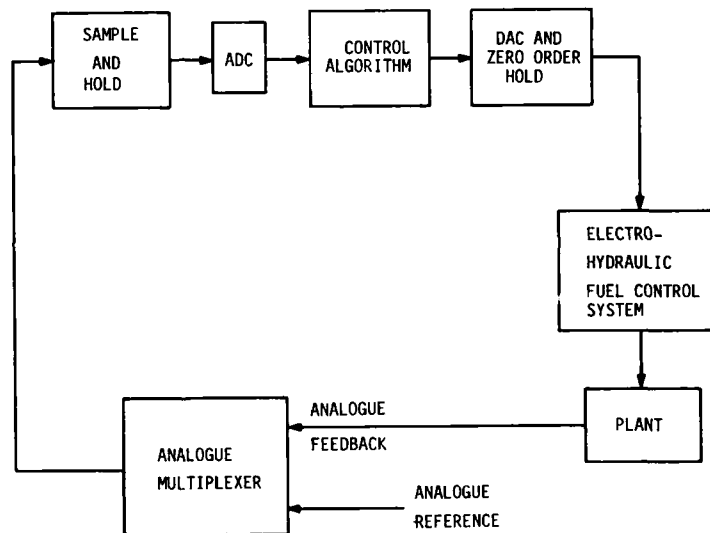


FIG. 6 SIMPLE CLOSED-LOOP DIGITAL CONTROLLER

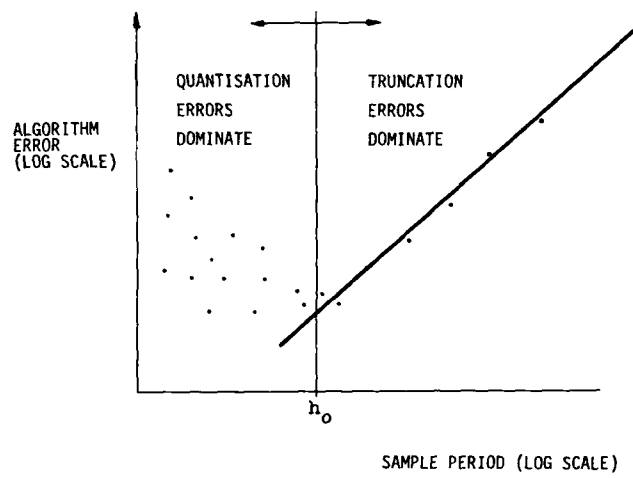
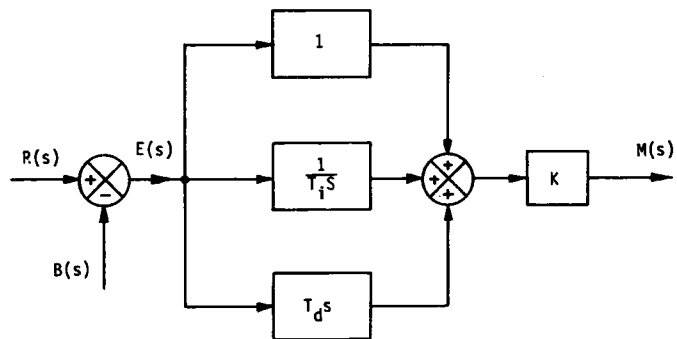


FIG. 7 TYPICAL RELATIONSHIP BETWEEN SAMPLING PERIOD AND ALGORITHM ERROR



$$\frac{M(s)}{E(s)} = K \left[1 + \frac{1}{T_i s} + T_d s \right]$$

FIG. 8 PARALLEL FORM OF P.I.D. TRANSFER FUNCTION

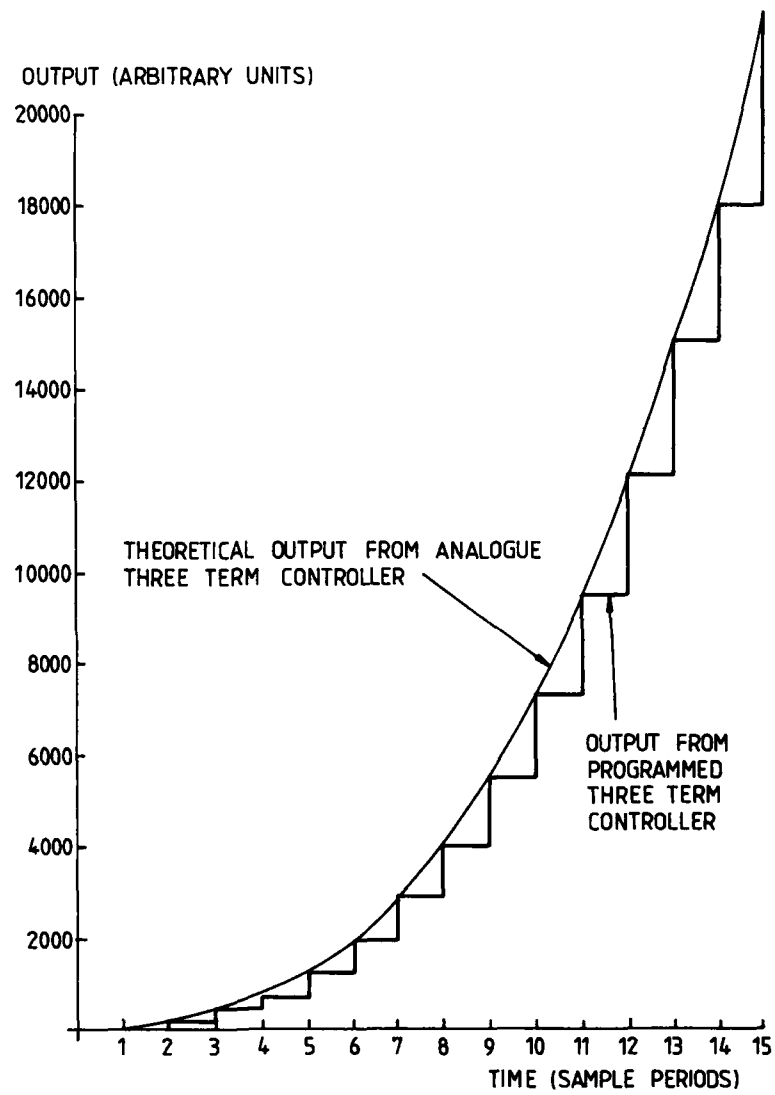
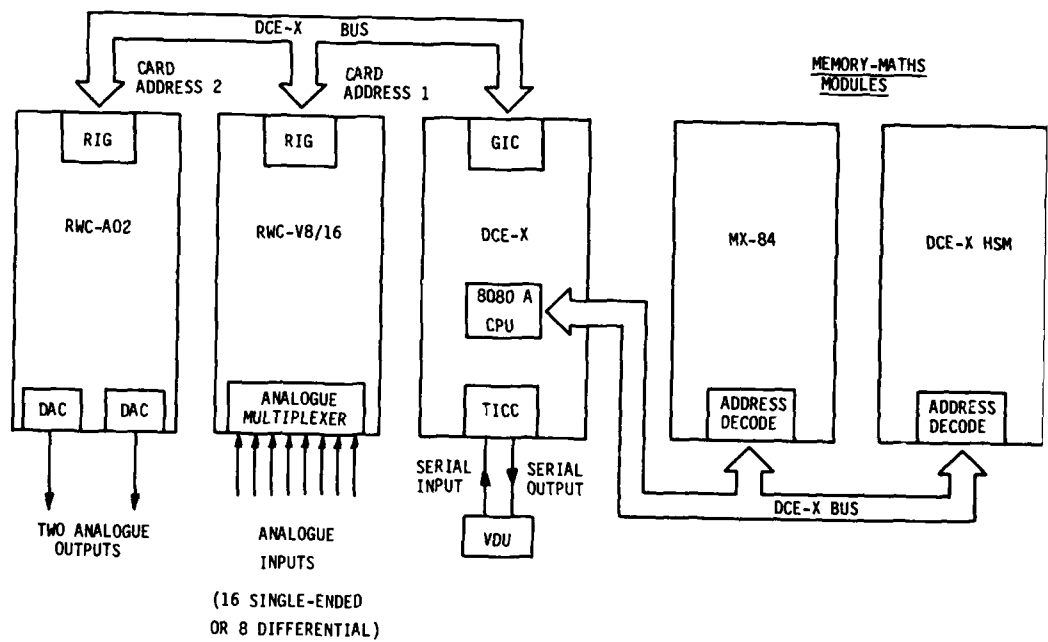


FIGURE 9 OUTPUT FROM DIGITAL THREE TERM CONTROLLER
WITH "ACCELERATION" INPUT

FIG. 10

HARDWARE CONFIGURATION USED IN PROJECT

72 3 02



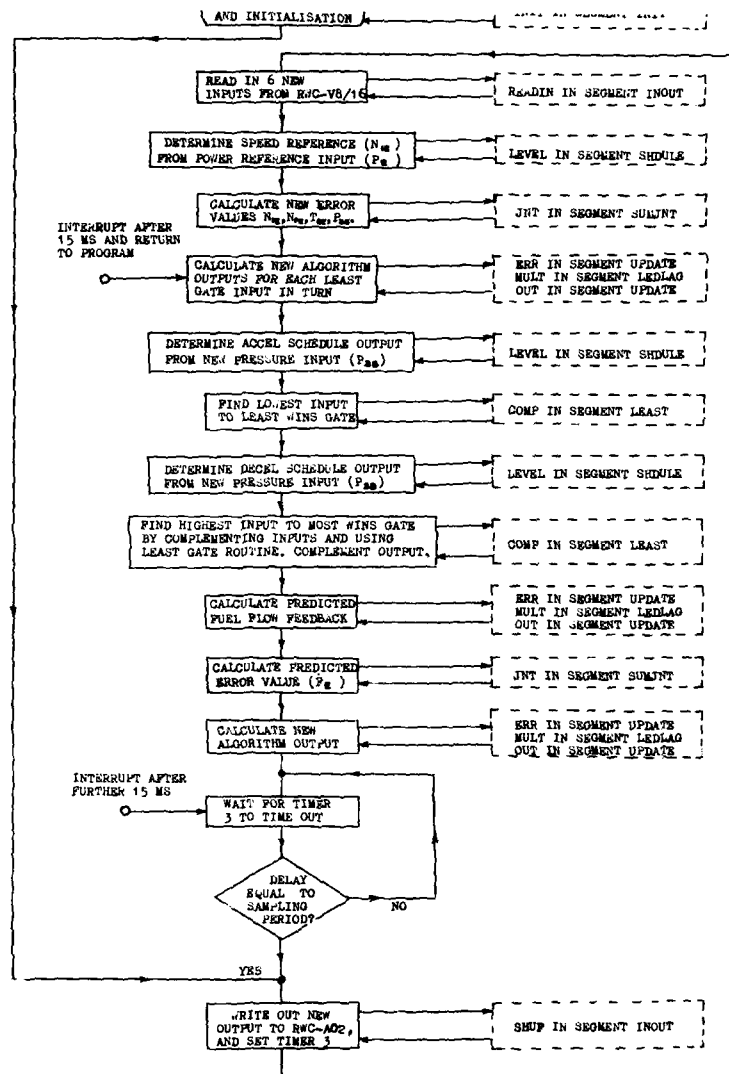


FIG.11 FLOW-CHART AT HIGHEST PROGRAM LEVEL (SEGMENT MAIN)

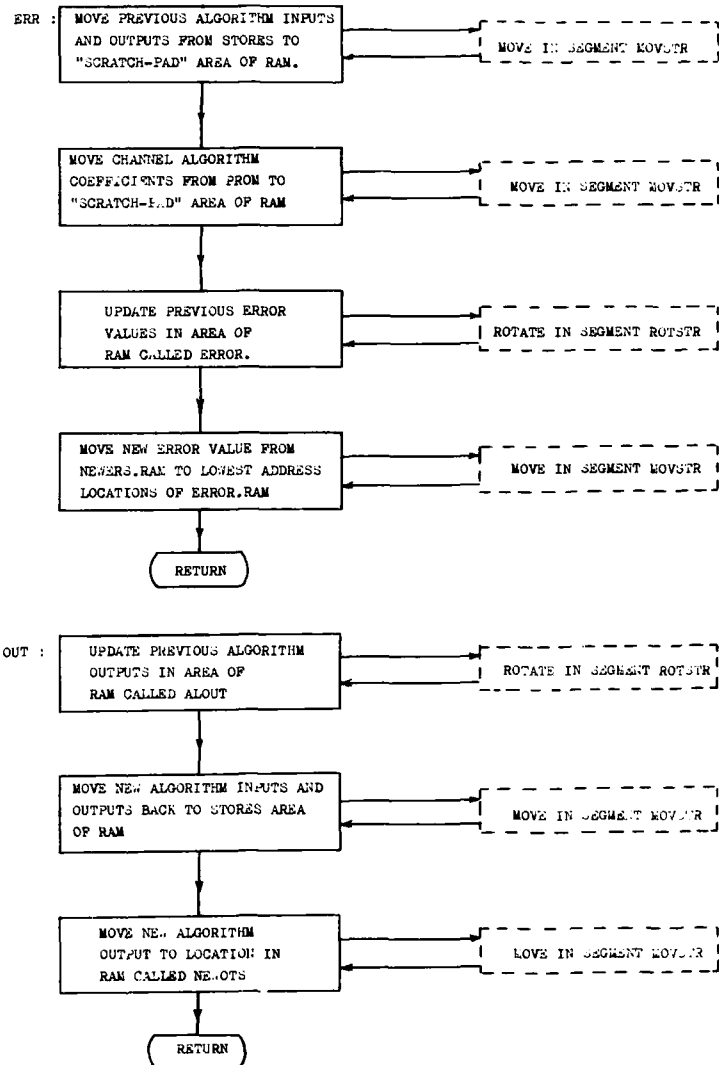


FIG.12 FLOW CHART OF SEGMENT UPDATE

```

10 /THIS SEGMENT CONTAINS THE ERROR UPDATE AND ALGORITHM
20 /OUTPUT UPDATE SUBROUTINES
30 /
40 /ERROR UPDATE SUBROUTINE
50 ERR: MVI B,10 /MOVE PREVIOUS ALGORITHM
60 LHL RUN.RAM /OUTPUTS AND INPUTS TO
70 XCHG /SCRATCH-PAD AREA OF RAM
80 LXI H,ALOUT.RAM
90 CALL MOVE.MOVSTR
100 MVI B,10
110 LHL RUN.RAM+2 /MOVE ALGORITHM COEFFS
120 XCHG /TO SCRATCH-PAD
130 LXI H,CONST.RAM /AREA OF RAM
140 CALL MOVE.MOVSTR
150 MVI B,04H /UPDATE PREVIOUS ERROR
160 LXI D,ERROR.RAM+3 /VALUES IN AREA OF
170 LXI H,ERROR.RAM+5 /RAM CALLED ERROR
180 CALL ROTATE.ROTSTR
190 MVI B,02H /MOVE NEW ERROR
200 LHL RUN.RAM+4 /VALUE TO LOCATION
210 XCHG /IN RAM CALLED ERROR
220 LXI H,ERROR.RAM
230 CALL MOVE.MOVSTR
240 RET
250 /
260 /ALGORITHM OUTPUT UPDATE SUBROUTINE
270 OUT: MVI B,04H /UPDATE PREVIOUS ALGORITHM
280 LXI D,ALOUT.RAM+1 /OUTPUTS IN AREA OF
290 LXI H,ALOUT.RAM+3 /RAM CALLED ALOUT
300 CALL ROTATE.ROTSTR
310 MVI B,10 /MOVE NEW ALGORITHM
320 LXI D,ALOUT.RAM /OUTPUTS AND INPUTS
330 LHL RUN.RAM /BACK TO STORES AREA OF RAM
340 CALL MOVE.MOVSTR
350 MVI B,2
360 LXI D,ALOUTN.RAM /MOVE NEW ALGORITHM
370 LHL RUN.RAM+6 /OUTPUT TO LOCATION IN
380 CALL MOVE.MOVSTR /RAM CALLED NEWOTS
390 RET

```

FIG. 13 ASSEMBLER LANGUAGE PROGRAM FOR SEGMENT UPDATE

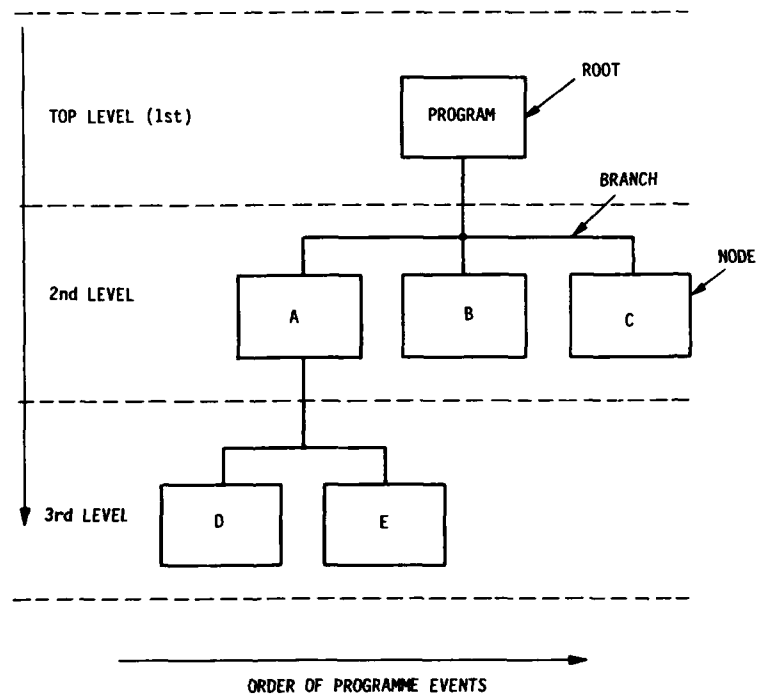


FIG. 14 A TYPICAL TREE STRUCTURE FOR TOP DOWN PROGRAMMING

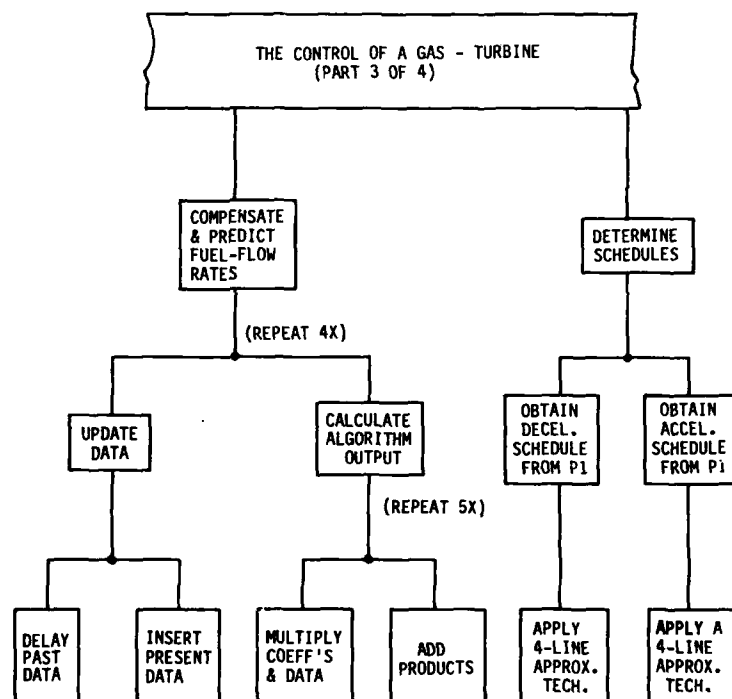


FIG. 15 TREE DIAGRAM FOR PART OF GAS TURBINE SYSTEM

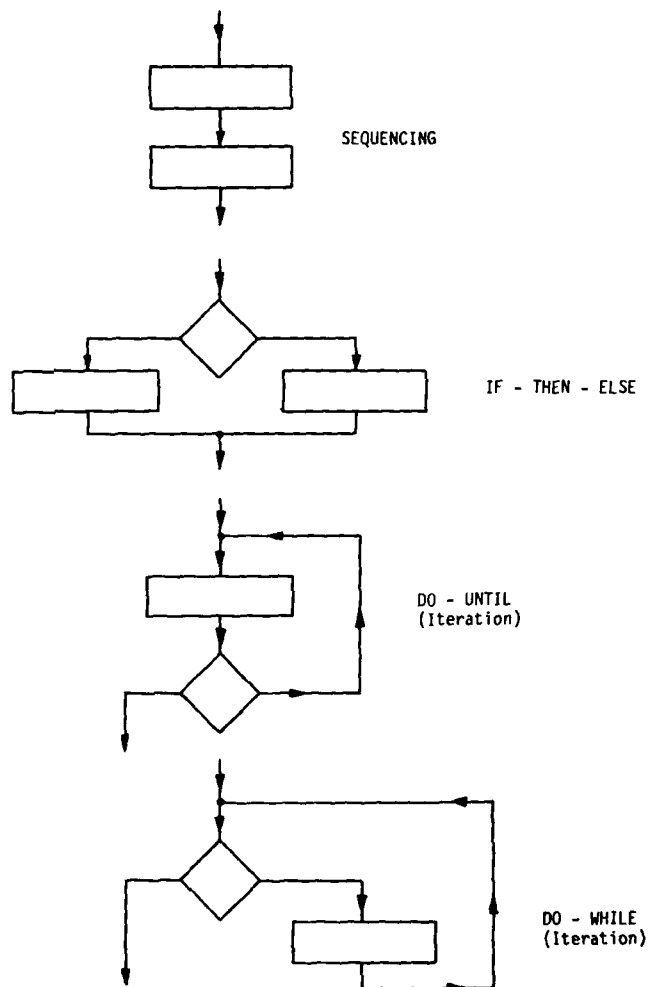


FIG. 16 THE CONTROL STRUCTURES USED IN STRUCTURED PROGRAMMING

```

/BEGIN//COMMENT//THE COMPENSATION AND PREDICTION OF THE FUEL-FLOW RATES FOR EACH INPUT EXCLUDING THE INPUT FUEL FLOW RATE AND POWER DEMAND;
/FOR/I:=1/STEP/1/UNTIL/4/DO/
/FOR/J:=5/STEP/-1/UNTIL/2/DO/PASTDATA(I, J):=PASTDATA(I, J-1); (THE PAST DATA IS EFFECTIVELY DELAYED BY ONE SAMPLE PERIOD
BY SHIFTING THE ARRAY CONTENTS)
/FOR/I:=1/STEP/1/UNTIL/4/DO/
/BEGIN//COMMENT//ENTERING THE PRESENT SAMPLE AND PREVIOUS OUTPUT INTO THE PASTDATA ARRAY;
PASTDATA(I, 1):=NEWERRORS(I);
PASTDATA(I, 4):=NEWOUTPUTS(I);
/END//OF PASTDATA MANIPULATION;
/FOR/I:=1/STEP/1/UNTIL/4/DO/
/BEGIN//COMMENT//THE NEW VALUES IN THE PASTDATA ARRAY ARE MULTIPLIED BY THE ALGORITHM COEFFICIENTS (COEFFS ARRAY) AND SUMMED;
NEWOUTPUTS(I):=0;
K:=#H0000;
/FOR/J:=1/STEP/1/UNTIL/5/DO/
HSM(COEFFS(I, J), PASTDATA(I, J), NEWOUTPUTS(I), K, NEWOUTPUTS(I), K);
(ALGORITHM COMPUTATION FOR ONE ERROR SIGNAL)
/END//OF ALL ALGORITHM COMPUTATIONS;
/END//OF DETERMINING THE FUEL FLOW RATES;

/BEGIN//COMMENT//CALCULATION OF THE ACCELERATION AND DECELERATION SCHEDULES;
/IF/INPUT(4) (ASBRK(1)/THEN/I:=1
/ELSE//IF/INPUT(4) (ASBRK(2)/THEN/I:=2
/ELSE//IF/INPUT(4) (ASBRK(3)/THEN/I:=3
/ELSE/I:=4
K:=#H0000;
HSM(ASM(I), INPUT(4), ASC(I), K, NEWOUTPUTS(7), K); (END OF A.S. OUTPUT CALCULATION)
/IF/INPUT(4) (DSBRK(1)/THEN/I:=1
/ELSE//IF/INPUT(4) (DSBRK(2)/THEN/I:=2
/ELSE//IF/INPUT(4) (DSBRK(3)/THEN/I:=3
/ELSE/I:=4; (START OF D.S. CALCULATION)
K:=#H0000;
HSM(DSM(I), INPUT(4), DSC(I), K, NEWOUTPUTS(8), K);
/END//OF BOTH SCHEDULE COMPUTATIONS;

```

FIG. 17 CORAL PROGRAM FOR FIG. 15

CENTRALISED CONTROL CONSOLE DESIGN

by Denis Lidstone
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Vickers Shipbuilding and Engineering Limited

ABSTRACT

The trend towards reduced machinery manning in warships has led to increased electronic complexity of system control and the need to optimise the Man/Machine Interface. This paper explores the problems associated with the design of a centralised control console for the propulsion machinery plant of a first-of-class vessel with unmanned machinery spaces.

From the initial design concept, an approach is proposed which benefits from the involvement and inputs of naval officers and specialists through to installation and test engineers, whilst retaining the degree of project control and phased design development essential to timely completion.

New developments are discussed which improve aesthetic appearance, aid operator efficiency and facilitate the accommodation of modifications at a late stage.

INTRODUCTION

Shipbuilders have been involved in the design and manufacture of control panels ever since the transition from sail to steam prompted the need for boiler controls and instrumentation. As ship systems were developed, so the quantity of controls and instrumentation and their layout became more complex until a control console - whether mounted locally within the machinery space or remotely on the bridge - became a standard requirement on all vessels.

In recent years there has been increasing emphasis placed upon reduced manning in vessels, and a growing trend to meet that requirement by adopting and developing the unmanned machinery space concept. This trend has been assisted and promoted by the rapid advancement of electronic technology which has been exploited to the point where a basic control panel has become a sophisticated control centre of such complexity that it is a major cost item. Furthermore, console design finalisation and ultimate construction has been so protracted by attempts to incorporate the latest developments and techniques that the item frequently becomes an unwelcome addition on the critical path of build and commissioning programmes.

This paper was conceived by design engineers with a view to informing interested parties of the state-of-the-art in centralised control console design and construction techniques as experienced within Vickers Shipbuilding and Engineering Limited; how it progressed to its present state over the past decade; the problems encountered and the way in which such console design and development projects are

K2-2



Figure 1 Control Console using Versatile Console Units

currently controlled and implemented by the Company against a background of continued technological advancement.

ESTABLISHED TECHNIQUES

A brief resume of current and past console building methods reveals that both excellent and less than ideal consoles have been manufactured, using a variety of techniques.

Versatile Console System

One of the earlier types of control console constructions used on naval vessels is the Versatile Console System (VCS) (see Figure 1). This extremely popular technique is still used extensively in operations rooms and bridges to group together what used to be miscellaneous boxes for radar, weapons, ship control etc.

The system utilises a framework constructed from standard sections of extruded aluminium with sheet metal top, sides and back, and is divided into standard sized 'boxes' on its operating face. Each box is a multiple of 6 inches in height and width, the depth being standard. By coded positioning of register dowels and sockets it can be made to accept any one of a large range of standard modular units. Cables from the rear sockets are run to a conveniently sited terminal chamber for connection to the ship's cables.

Such consoles are very flexible, since a faulty module can be simply unplugged, or a position modified easily by the substitution of an alternative standard module without affecting the remainder of the console's units; minor adjustment to the internal wiring and repositioning of the registration dowels is generally all that is needed to complete the change. This construction is particularly useful where access to the rear of a console is limited or non-existent, since wiring and sockets are reasonably accessible from the front.

Consoles adopting this modular concept are generally pleasing to the eye, but do not easily lend themselves to achieving optimum ergonomic layouts. For example, it is difficult to optimise the position of a single switch, since it can only be brought to the preferred location by ensuring that the module containing that switch is at that location, and this will invariably have an adverse influence on the siting of other modules. Whilst not so important in some applications, this does present a particular drawback when designing machinery control consoles.

Another known limitation with VCS units is the tendency to duplicate equipments which is often unavoidable, eg when they have their own built-in power supply. Space limitation is another restriction to the designer, since expansion is always by a fixed amount to accommodate the standard modules.

Finally, the extensive use of mimics is generally precluded - although some modules do use them to identify particular functions. In the case of machinery control consoles, where high packing densities are required, this could present a particular limitation and incur additional costs in developing the standard range to cater for such applications.

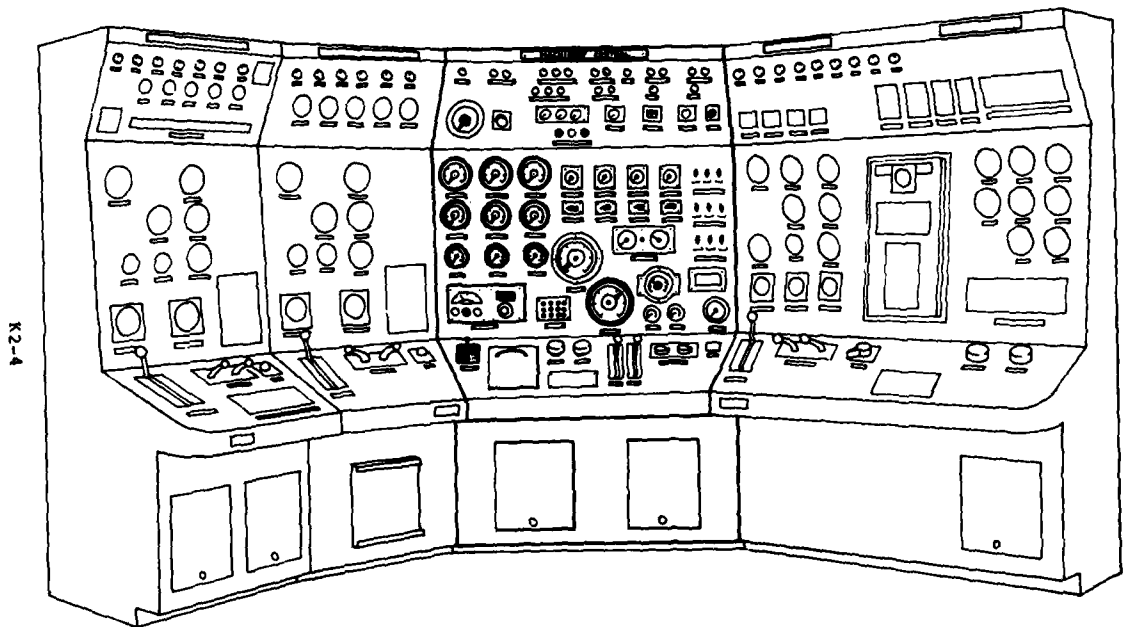


Figure 2 Typical Early Machinery Control Console

Notwithstanding these drawbacks, the VCS system remains popular, particularly where standard modules are applicable to many control positions.

Other Modular Systems

Similar modular systems are used for the control of auxiliary machinery, eg air compressors, diesels, air conditioning plants etc, and whilst many of the comments made against the VCS approach are equally applicable here, these consoles have the added disadvantage of tending to be rather large. Whilst this may not always present a problem, it is invariably found that in such consoles using the 'standard building block' approach, the utilisation factor for certain units is extremely low. This often results where insufficient funding has been made available to develop a system with inherent flexibility to accommodate new plant configurations.

Machinery Control Console Layout

Early machinery console facia layouts tended to have controls and instrumentation grouped locally or remotely in what often appeared to be no logical sequence (see Figure 2). Careful examination or, perhaps, familiarity by operators would reveal a form of grouping, but the sheer number of meters (often of different size, closely grouped and including both direct and indirect reading gauges) did nothing to aid the operator in terms of his response or efficiency.

More recently, the trend has moved towards the adoption of standard electrical components with particular emphasis on logical grouping and the use of passive mimics. More consideration is given to the operational and ergonomic aspects, but the results fall far short of the optimum. With the increase in and complexity of modern control and instrumentation, the need to optimise centralised console designs has become essential, particularly if reduction in the number of watchkeepers is to continue.

INPUT FROM QUALIFIED PERSONNEL

Who is the expert in console design? Some would argue the user, others the various design authorities, whilst some would say the whole thing is overrated and leave it to a manufacturer, having given him a basic statement of requirements.

With the degree of sophistication now reached, it is essential to tap the expertise of numerous personnel in order to optimise the design. That is not to say we should design by committee, but that all aspects relating to the console should be carefully considered by obtaining advice from all those with a valid contribution. By sensibly assessing such advice and compromising as necessary, the optimum end product should evolve from this iterative design process.

Let us now consider who the experts are and what contribution they can make.

Experienced Naval Officers

Typically these will be Engineering Officers of the Watch with many years experience, particularly in the class of vessel being considered. Such persons can advise on traditional methods of operating plant, standard operating procedures (where applicable) and limitations of existing plant control/monitoring systems. The latter aspect is an essential feedback to the project and answers such questions as 'Was there insufficient monitoring at the central position?'; 'Why were certain facias considered poor?'; and 'Did operators have physiological problems with certain aspects of an existing console?' The resultant observations, coupled with comments on the early sketch design for the proposed consoles, make an invaluable contribution to the design process.

Ministry of Defence Engineers

These engineers produce the Staff Requirements for vessels and are responsible for overall project management. Ministry personnel engaged on a project should have access to numerous specialists within Government departments and therefore be in a strong position to advise or make decisions in the event that a compromise in the overall requirement becomes necessary.

Ministry Consultants

In certain circumstances, the MOD may wish to use consultants for advice on early conceptual ideas and to maintain a watching brief to ensure that the objectives are carried through. Such groups can be extremely experienced and usually employ ex-Naval staff. If a shipbuilder lacks the necessary design team, the responsibility of such groups can effectively be extended as a sub-contract from the Ministry staff responsible.

Console Manufacturers

In-depth knowledge of manufacturing detail must lay with the console manufacturers themselves and their early involvement can only be to the advantage of the project. This might seem difficult to implement without prejudicating the final contract award, but in practice it has been found to work well. A small contract is usually sufficient to cover the cross checking of manufacturing design concepts or to fund a small design study.

Shipbuilder's Design Teams

Where such teams exist within a shipyard one will usually be installed as Project Management for the Console. This team will hopefully have many years experience and be able to assimilate the information being fed in by the personnel already mentioned and to formulate a design that meets the stipulated requirements. The strength of such design teams lies in the in-house support they are able to obtain from those working at the 'coal face' on installation and commissioning. These two areas are all too often overlooked and, if not considered, can result in numerous through-life problems, eg layouts of internal components, method of cable entry and terminal chamber layout, shipping to position, documentation standards, etc. Such topics are perhaps mundane in themselves, but are all essential ingredients to a successful design.

An ongoing part of a shipbuilding designer's function is that of associating with a steady flow of ships' staff, and he should use this opportunity to obtain their reactions to current designs and trends.

It is submitted, therefore, that all (or the majority of) the forementioned personnel groups are necessary to produce a satisfactory design.

INITIAL DESIGN CONCEPT

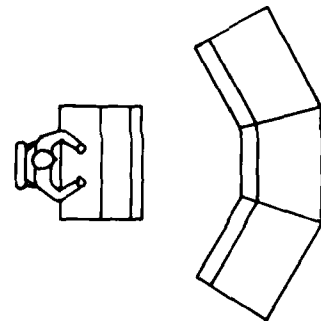
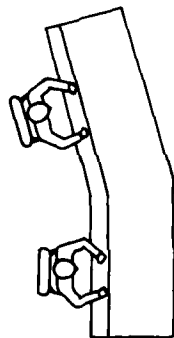
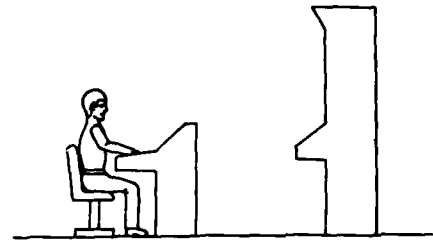
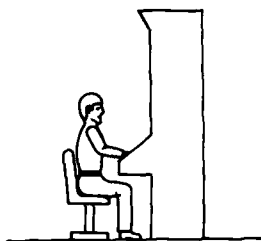
Formulation of Design Philosophy

The start point must be the Staff Requirements' target figures, etc, from which the sketch design for the overall control and surveillance of the machinery will ultimately evolve. The aspects to be ascertained at this stage will include the following:

- (a) Number of Watchkeepers per watch and their proposed distribution throughout the plant, eg unmanned machinery spaces, and the differences between, say, Manoeuvring and Harbour State.
- (b) Type of Propulsion Plant and its operational philosophy, eg remote and local control arrangements.
- (c) Philosophy of auxiliary machinery operation, eg will such plants as auxiliary boilers and air conditioning have remote monitoring/shut down with local start up and control?
- (d) What is the Control/Surveillance philosophy? The extent of computer control and monitoring and the extent of hardwired instrumentation is an important factor which must be considered. It is particularly relevant when considering operational aspects during failure situation, eg should there be sufficient hard-wired instrumentation to safely control the plant on failure of any computer-based surveillance system and what additional watchkeepers would be required?
- (e) Is there a need for additional automation of plant to meet the manning requirements, or would the maintenance aspects create an unnecessarily high work load?
- (f) Operators' responsibilities need to be carefully considered, with a typical arrangement being:
 - (i) Electrical Generation and Distribution
 - (ii) Propulsion
 - (iii) Secondary Plant
 - (iv) Damage Control
 - (v) Supervisor

Obviously, the split of responsibilities is seldom as simple as this.

K2-8



(a) Single Tier Console

(b) Two Tier Console Configuration

Figure 3 Typical Console Configurations (Conceptual Design Stage)

- (g) What configuration of console is appropriate in the situation being considered and does it fulfil the normal training/ advancement policy requirements of the Navy?

It is appreciated that many of the above are interrelated and will need careful consideration, with much iteration, before a clear picture on the type of control requirement emerges. It is important that such decisions are made as early as possible in order that a firm basis can be established.

Establishment of Firm Draft Basis

At this point in the design process there will be no mechanical or electrical schematic diagrams on which to base console size; however, estimates will be necessary to produce the first sketches of the console and to ensure that sufficient space has been allocated in the Machinery Control Room. Early estimates must, therefore, be based on experience, coupled with the answers to the philosophy questions already mentioned, plus the additional area necessary to cover the normal increase in instrumentation as the detailed design proceeds.

It is at this stage that the first facias drawings are produced to confirm the areas originally estimated from the first general arrangement sketches which were produced from experience.

Whilst not essential at such an early stage, the manufacture of a full-size wooden mock-up of the console suite has certain advantages. The use of a mock-up is one of the most powerful tools to the console designer since it provides the necessary 'feel' for what he is trying to create. The full advantages of a mock-up will be enlarged later, but its availability at an early stage offers the following possibilities. It:

- (a) gives a three-dimensional console with paper facia drawing which enables those involved in the philosophy to review their decisions;
- (b) enables an extension of the early work, particularly in fields of operating philosophy, by allowing the operators to sit at the console and determine the workload demand placed on them during both normal and emergency operating procedures;
- (c) assists in the assessment of panel construction techniques and such areas as natural breakdown of the suite, suitability of facia angles from incident light aspects etc.

Figure 3 illustrates the types of console configuration that could emerge from such an exercise and shows the scope that exists in control console arrangements.

It is assumed that, in parallel with the above work, a similar approach for other areas of the naval vessel has been adopted for such topics as compartment configuration, siting of major equipments and detail of the propulsion plant and auxiliaries. That being the case, the end of this 'phase' should have established a firm draft design basis from which to proceed.

REVIEW OF CURRENT/PROJECTED TECHNIQUES AND COMPONENTS

The review of components and techniques to be adopted should be a continuous activity, keeping abreast of current developments and reviewing existing methods with a view to improvements. This is an extremely important activity, since the potential saving in manufacturing time and improvements in both display presentation and overall reliability can be high. It is always difficult to justify the cost-effectiveness of such activities, but listed below are some of the questions and investigations that should be continuously addressed, followed by descriptions of areas for particular attention and concluded by examples of recent developments.

Areas for Review

- (a) Review existing and new facia components in terms of reliability, viewing distance, flexibility, cost etc.
- (b) Review the type of existing and new internal components in terms of reliability, size, cost etc.
- (c) Can overall constructional techniques be improved?
- (d) What new materials are there available and will they overcome limitations of existing materials?
- (e) Can internal component mounting be improved, particularly with the increasing amount of electronic circuit boards being housed within the console and can easy access for commissioning/maintenance etc be maintained?
- (f) Review the configuration and size of terminal chambers, the type of terminations and the method of entering and supporting ship-builders cable.
- (g) Review new wire standards and their effect on installation, coupled with improved methods of internal loom configuration and the use of plugs and sockets.
- (h) Can new types of displays be easily adapted to meet the environmental and operational requirements, eg Visual Display Units, Linear Analogue Displays?

Consistent Policies

During these considerations, the Design team establishes a consistent operating policy as to types and manufacturers of components, in order to ensure a uniformity of approach, ie all illuminated pushbutton switches to be of Messrs X's manufacture; all meters to be of Messrs Y's 50mm range. This policy can be as a result of a maintenance/spares philosophy based upon a preferred range to a known specification, or arising out of experience, but it enables the panel layouts to be drawn reasonably accurately, and checks to be made for accessibility etc.

At the same time, basic decisions are taken as to the type of control to be afforded - for instance all controls to be by pushbutton instead of rotary switch; all instruments to be nominal 50mm dia, 240° movement, with white lettering on black scale etc.

Particular Areas of Constant Concern

The beginning of a new contract is the most important time to review current techniques and components used, and to assess feedback from consoles already in use and those currently under construction. Criticism of software standards has been a continuous discussion point amongst manufacturers, installers and commissioning staff alike - the need to establish the correct standard being vital to such a project.

The need for a base document such as a schematic diagram to define all wiring within a console and its relationship with the rest of the system is essential, particularly with very complex control consoles. Once completed, such a base document enables console/equipment manufacture and the installation of cabling to proceed with confidence, and enables a clear understanding of the system to be made.

Detailed System Design

It is essential that documentation standards follow the systems design drawings in order that any component shown thereon and mounted in or on the console is correctly identified, both on the systems drawings as to type and make etc, and on the console drawings as correctly identified references. Thus, the cooling water system may include a pushbutton switch (Ref PBS3) which must be shown on the drawing as 'Messrs X mfr. type 123/4', whilst the appropriate Facia Panel must have the same switch identified as 'CW/PBS3'.

Obviously, occasions will arise when the standard range of components adopted by the console team will not meet the particular requirements of a system. At this point, discussion between the designers results in a suitable alternative being selected, and the Facia Panel drawing must then be corrected as required to show this non-standard component.

It is worth mentioning that experience has shown the desirability of standardising on particular ranges of components. Thus push-button switches tend to be of only two types - intermittent or latching. All are illuminated, and all are 4-pole, 2-way, form C. Similarly, lamp indicators are of the same range as the switches. Relays for low-voltage use are generally 4-pole crystal can pattern. For up to eight poles, two relays may be connected in parallel and only for special coil voltages, contact currents, or large numbers of contacts are specially-selected relays used. This standardisation not only lessens the chances of error in component selection and simplifies the draughting work in panel layout, but also eases the problems of maintenance and spares.

Awareness of New Developments

Whilst this refining and cross-checking of techniques continues, the Console Designer must also be aware of new developments in allied fields which would have a bearing on console layout. For instance, he might be aware of a new system being developed elsewhere within the Design Office which, if installed on the vessel carrying the console, would require a VDU to be installed on the facia and possibly require additional internal rack space.

K2-12

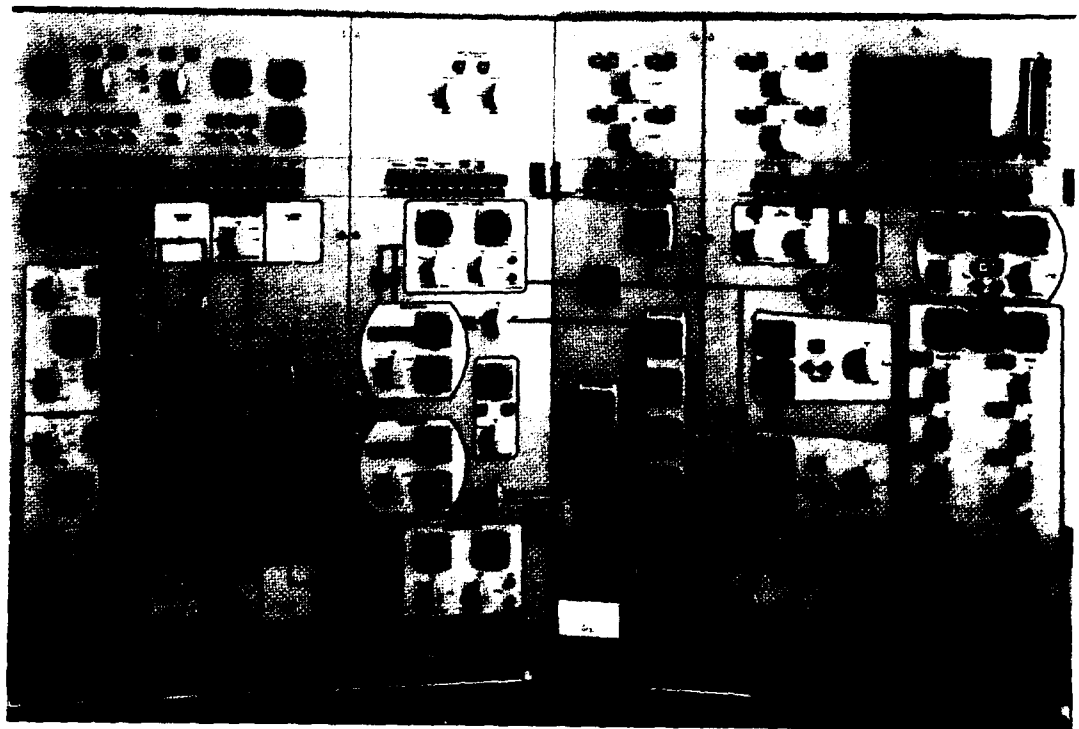


Figure 4 Illuminated Miric Facia

Such developments must be considered carefully and on merit, and due allowance made within the console. A 'for but not with' design can always avoid future refit problems, but must be balanced against the need for space to be used efficiently in the first instance.

Physical Size

One thing the design team must not overlook is the actual size of the facia panels. For some time now it has become usual to make connections between hinged panels and console by means of plugs and sockets. This allows faulty or obsolete panels to be easily changed if necessary, even at sea. However, any oversize panels should be considered separately, since it is futile to be able to speedily replace a complete panel if the replacement cannot be brought through a door without opening-up special shipping routes.

Initial Contact with Component Manufacturers

By the time the design is approaching completion, the engineer will start discussions with the major component suppliers and potential manufacturers. Usually such manufacturers are only too pleased to be involved at this stage, since it gives them an opportunity to prepare details of all required items, check their production facilities and delivery programmes, and draw up a formal quotation for submission in due course. Often such contact has resulted in the manufacturer allocating a special reference number to all components for the contract and any requests for non-standard parts or 'specials' have been sympathetically considered. Finally, the person-to-person contact between the engineer and the representative is vital for resolving future problems should they arise.

Recent Improvements

Two areas of improvement recently made are those of console facia construction and the use of illuminated mimic techniques (see Figure 4).

With increased instrumentation packing densities on facia panels, the use of mimic diagrams and in certain areas illuminated mimics, has become essential to give clarity of controlled viewing. The standard construction now adopted is that of an aluminium back-panel with a polycarbonate facia overlay. The aluminium is the strength member whilst the clear overlay is screen-printed on the back to give the necessary flow lines and plant shape grouping. The two units are then machined to allow fixing of facia components, hinges, wiring loom support studs etc. Such a technique has advantages in that any combination of colour can easily be accommodated; quite major changes to both facia and back panel can usually be made without the complete remanufacture of the items; and the appearance of the facia is pleasing, durable, and easily cleaned.

The illuminated facia uses exactly the same two-part construction, but the aluminium is milled to allow the inset of Perspex light guides. By securing lamp holders through the aluminium into recessed holes in the guides and by suitable screen-printing, and colouring of the Perspex guide, the appropriate flow line can be illuminated.

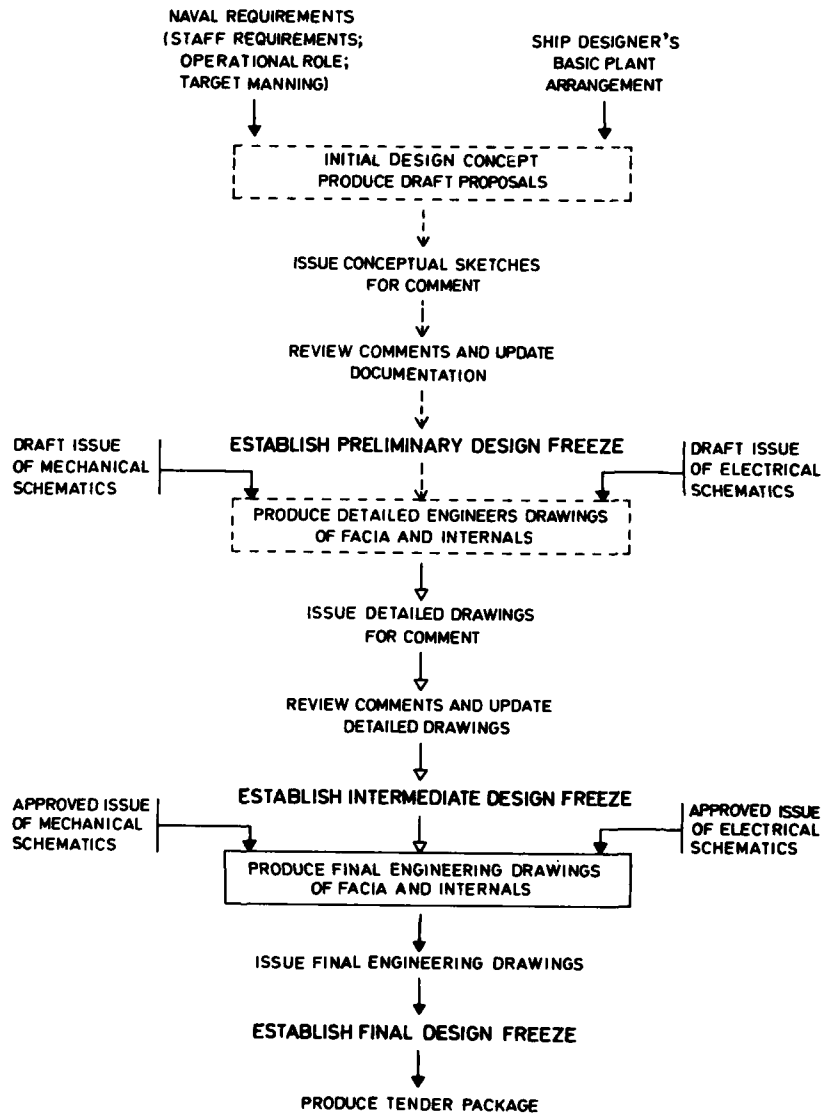


Figure 5 Proposed Design Sequence
R2-14

A further technique currently being developed is the use of fibre optic illumination to replace the lamps, fed from two sources per panel facia. Each fibre bundle per flow line is controlled through a liquid crystal matrix shutter, thus enabling each flow line to be switched on and off independently. It is believed that this technique is now perfected and will be offered for shipboard use in the near future. The main advantages of this approach are:

- (a) reduced maintenance, eg no lamps to be replaced;
- (b) reduced heat dissipation within the console, particularly at the facia;
- (c) accessibility of main lamps against that of individual lamps at rear of facia;
- (d) flexibility of facia arrangement, since less space is needed to accommodate fibre lamp holders;
- (e) mimic drive logic is easily configured in semi-conductor logic

A detailed appraisal of both the facia panels and the illuminated mimic technique is provided in Appendices 1 and 2 to this paper.

FREEZING THE FINAL DESIGN

The timescales for the various phases of console development are dictated by the overall programme for the ship and, therefore, ideal approaches may not be possible. Having established the conceptual aspects and perhaps produced an initial mock-up as suggested earlier, there must come a time when a 'design freeze' has to be implemented. But what does a design freeze mean and when should it be implemented?

It has been found in recent contracts that the Machinery Control Console programme has been on the critical path and consequently has driven the timescales of supporting activities. Whilst wanting to freeze all aspects as early as possible, it is important to be realistic, since the rushing of design groups to finalise their activities may only result in oversights and the need to introduce 'essential' changes at a much later date.

The sequence described herein, and shown in flow diagram form in Figure 5, is a method of working now considered the best compromise in meeting the numerous constraints. It assumes a new class of Control Console relative to a first-of-class vessel.

Experience has shown that there are certain milestones that could be considered as interim design freezes before the final freeze is met. The definition of these milestones is as follows.

Preliminary Freeze

This follows the completion of the conceptual aspects of the console, and in the case being proposed is concluded by the approval of the first full-size mock-up inspection. What has been established by this stage is as follows:

- (a) agreement on the console envelope and individual split of instrumentation into panel sections;
- (b) agreement on the control philosophy and the volume of control and instrumentation required;
- (c) Naval Operational requirements have been met regarding numbers of watchkeepers and promotional progression;
- (d) agreement on general component and constructional techniques.

The end of this phase corresponds roughly with that stage in the design process already described under the 'Formulation of Design Philosophy' heading. In practice, there are no obvious break points when all these tasks have been reviewed and solutions or agreements reached. Indeed, certain controversial points may well be carried over into the intermediate design phase.

Intermediate Design Freeze

Following the above phase, the detail system design commences, although, hopefully, it has already started. It then becomes important to complete the first issue of the Electrical System Schematics in order that preliminary detail design can start.

On achieving this freeze milestone the following should be complete:

- (a) facias should be updated to a realistic datum to reflect the systems being controlled;
- (b) facias should be laid out in an ergonomic manner to take account of the engineering aspects eg component spacing console framework;
- (c) the console envelope size is confirmed;
- (d) allocation of space for major components within the console to a first approximation;
- (e) a set of engineering drawings issued for comment.

Upon receipt of agreed comments, drawings will be suitably updated and the Design Freeze established. As with the Preliminary phase, there will always be a few outstanding points to carry over to the next phase.

Final Design Freeze

During the Intermediate phase, the first issue of engineering console drawings were produced and comments received from the relevant authorities, eg MOD and Navy. In parallel with this, Electrical and Mechanical Systems Schematics will have been raised to Approved Issue level. Assuming that these two sources are correctly correlated, the Final Design Freeze should be implemented as follows:

- (a) finalise the facia layouts;
- (b) finalise the volume of control equipment to be sited within the console;
- (c) finalise the allocation of space within the console for the equipment in (b);
- (d) issue Final Engineering Drawings.

Comments on the Sequence of Events which led to the Final Design Freeze.

The design sequence described is an idealised approach, since it assumes that time is available for such a long-winded process. In practice, the Intermediate phase is rarely recognised and usually blends with the Final freeze, although updates of facias with revised systems information do take place.

It is also found that certain systems lag behind in development, either from complexity, uncertainty in other related mechanical areas, or constant changes from customer or design authorities. In such cases it is sometimes necessary to make 'best guess' solutions in order to progress, which tends to undermine the whole concept of a phased freeze approach.

Other pressures may mean the placing of contracts to enable a console manufacturer to proceed before such freezes are reached; again this is not satisfactory and may incur additional costs. As already stated, the designers should be conscious of such problems and try to improve manufacturing/design techniques to enable the Final Design Freeze date to be as late as possible.

Another possibility is that breakdown of the console is so arranged that individual sections may be treated separately during the freeze sequences. This is particularly true during the early stages and for facia arrangements, but the amount of interdependents will place constraints on this approach. It is true to say that the finalising of systems will vary with, say, the Power Distribution System being ahead of the Propulsion System.

Finally, it must be realised that a Final Design Freeze is an idealised target which will rarely be achieved, but the percentage completion should be as high as possible in order to reduce resultant problems in the detailed design and manufacture stage.

THE TENDER PACKAGE

At some stage dictated by the programme the need will arise to obtain quotations from potential suppliers. If the number of these suppliers is high, then it will almost certainly be necessary for a preliminary tender package to be produced and forwarded to them for

their consideration. This will enable an assessment of each supplier's capability and budget costs to be made and a short list drawn up. Assuming this approach is to be adopted, the following actions will be necessary.

Preparation of Preliminary Tender

The earliest stage time which is practicable for this exercise is at the end of the Preliminary Design Freeze. By then the envelope size, facia arrangements and general construction techniques have been determined but this information will have to be supplemented by additional guidance if a realistic assessment is to be made. The Preliminary Tender package would consist of:

1. General Arrangement Drawing.
2. Facia Arrangements Drawings.
3. General Arrangement of major internal components and their positions.
4. Estimate of internal system complexity (This is obviously based on experience and would be a list of numbers and types of components, numbers of wire ends etc.)
5. First draft of the Constructional Statement of Requirements which should detail all relevant specifications, constructional standards, special requirements etc.
6. Cost Control and Contractual Requirements.
7. Documentation Standards.
8. Delivery Dates.

Whilst being an extra stage in the procurement process, it does enable a realistic assessment to be made of each company - quoting against the same provisional specification. Careful analysis of the replies is essential, since the quotations will give a budget price only.

Preparation of Main or Final Tender

The main tender exercise should take place after the Final Design Freeze when all the preliminary tender information is available and the console has been fully defined. At this stage a fixed-price quotation should be possible but, here again, the exclusions to that price must be clearly defined and understood.

The Final Tender package will be as follows:

1. Approved General Arrangement Drawings.
2. Approved engineering type Facia Drawing.
3. Details of all major internal components and their positions.

4. Approved Electrical Schematic Diagrams to cover all circuits within the console.
5. The final Statement of Requirements, which includes:
 - (i) Standard Specifications which be followed.
 - (ii) Constructional Standards.
 - (iii) Special Requirements, eg breakdown of console suite, screening, fire prevention.
 - (iv) Environmental Standards.
 - (v) Types of Components.
 - (vi) Facia mimic colours.
 - (vii) Free issue items.
 - (viii) Cost Control.
 - (ix) Documentation Standards (examples must be provided for clarification purposes).

Contractual Clauses

In-depth discussions may be necessary to ensure that each potential manufacturer has fully understood the requirements and that each exclusion is clearly identified. An area which is particularly difficult to assess is each manufacturing company's ability to undertake the contract. Designers personal experience in their dealings with companies on earlier contracts plays a large part, but discussions regarding manufacturers' workloads during the contract period and the resources they can make available must take place in an attempt to guarantee timely completion. The outcome of all this work will be a recommendation to the customer on the supplier to be used.

It must be said that the foregoing represents the ideal approach and on certain occasions the Contract must be awarded before the Final Design Freeze. In such circumstances the contract would be placed against a budget price and progress monitored using a Development Cost Plan (DCP). A detailed understanding of the work yet to be carried out would be essential, and the change-over to a fixed-price contract should take place as soon as possible after the Final Design Freeze is established.

Table 1 Schedule of Queries and Changes

PROJECT:- XKR TTY CONSOLE										
SCHEDULE OF QUERIES & CHANGES										
SUBJECT	DATE RAISED	ACTION TO NAME	DATE	CLEARED BY NAME	DATE	W/O AFFECTED	D.C.R. N° IF APPLIC.	EFF ON CONT. OR PROJ. COST	OR PROJ. DELAY W/O	
6A. ELECT. PANEL R/H FACIA ARE FOLLOWING PLANT SHAPES TO BE ILLUMINATED OR NON-ILLUM? ELECT. SYSTEM ALARMS E.F.C. REMOTE START EARTH TEST FACILITY ALL TO BE NON-ILLUMINATED.	19-12-79	A. ROWLANDSON	19-12-79	TELECON.						
6B. M.C.D. LAYOUT ISSUE B DATED NOV 79 QUERIES										
1. FUSE CARRIERS & BASES CALLED 'F' IN GEN. NOTES BUT NOT SHOWN IN LAYOUT? 20 PAIRS OF FUSES WILL BE REQUIRED.	31.1.80	J.N.C.	31.1.80	J.N.C.	31.1.80					
2. THE SIZE 3U CARD RACK SHOWN IN L/H SECTION WILL NOT PERMIT WITHDRAWAL OF CARDS DUE TO PROXIMITY OF SERVICES PANEL ALLOW RACK TO PROTRUDE INTO CENTRE DESK AREA	31.1.80	J.N.C.	31.1.80	J.N.C.	31.1.80					
3. R/H PANEL SHOWS SHIPS CABLING BUT NOT TAPER PIN BLOCK MOUNTING PANEL. NO SHIPS CABLING IN R/H PANEL	31.1.80	J.N.C.	31.1.80	J.N.C.	31.1.80					
4. R/H PANEL NOTE CALLS FOR HINGED FRONT DOORS BUT IT WAS AGREED AT MEETING ON 1.11.79 THAT THESE DOORS COULD BE RETAINED BY QUICK RELEASE 'CAMLOC' FASTENERS CONFIRM QUICK RELEASE 'CAMLOC' FASTENERS	31.1.80	J.N.C.	31.1.80	J.N.C.	31.1.80					
5. THE VOLT. TYPE PD3500 IS SHOWN IN CATALOGUE AS 14" 10 1/4" DEEP, WITH 1 1/2" CLEARANCE FOR EXHAUST & INLET FILTERS. LOCAL 'BLISTERS' WILL BE REQUIRED AT R/H END FOR CONNECTORS 'BLISTERS' OR 'TOP HATS' APPROVED BUT SUBJECT LEFT OPEN FOR FURTHER STUDY REBOARD FOR PD3500 IS 19" WIDE & WILL NOT FIT AS SHOWN ON R/H PANEL DESK FRONT REBOARD WILL BE 'SPECIAL' TO FIT DESK FRONT.	31.1.80	J.N.C.	31.1.80	J.N.C.	31.1.80					
6. HEIGHT OF LSI-11 MICROPROCESSOR SEALS 21" 25" ON LAY-OUT BUT IS SHOWN AS 27" 75" IN PLESSEY CATALOGUE STILL TO BE CHECKED BUT IF 21" 25" DIM'S ARE CORRECT, STANDARD UNIT WILL HAVE TO BE MODIFIED.	31.1.80	J.N.C.	31.1.80	J.N.C.	31.1.80					
				J.N.C.	25-1-80					

K2-20

VICKERS SHIPBUILDING & ENGINEERING LTD.					
Barrow Shipbuilding Works					
CLASS OF VESSEL	XYZ	DESIGN CHANGE	ESP Change	BOAT No.	FORM No.
				1122	29
CONTRACTOR: Blagden Switchgear Limited				ISS. No.	01
SYSTEM / EQUIPMENT:		Centralised Control Console		ORDER No:	DATE:
				P/1234/5	11/10/80
CHANGE DETAILS:					
This Change Form is raised to take account of modifications requested in VSEL letter 12/9/80:					
(a) Move switches M/S34 and M/S35 from LH Facia to Desk.					
(b) Delete meter SW/M21 from LH Desk.					
(c) Additional wiring required for 10 new alarm circuits.					
DRAWINGS AFFECTED:					
Facia Layout AO/11211					
Desk Layout AO/11215					
Wiring Schedules A3/23513, 23514 and 23515					
CONTRACTOR TO COMPLETE					
COST	E471	EFFECT ON PROGRAMME	1 week delay	OTHER ORDER EFFECT ON COST.	PROG.
COMMENTS (Use over page if necessary):					
Drawing Office E231					
Engineering 120					
Materials 120					
E471					
REF: SCL/1122/98765		DATE: 12/10/80		SIGNED: <i>[Signature]</i>	
APPROVAL / COMMENTS					
U.S.E.		M.O.B. (PEI)		FINANCIAL LIMIT:	
Approved <i>[Signature]</i>		Approved <i>[Signature]</i>		FORM No.	
REF: V/262/58		DATE: 20/10/80		29	
				ISSUE No.	
				01	

Figure 6 Typical VSEL Change Form (Reduced size)
K2-22

Because the manufacturer will not necessarily commence work on each section simultaneously, it may be possible, through discussion, to manufacture potential problem panels as late as possible. Whilst this presupposes some goodwill on behalf of the manufacturer, it can possibly save him the frustration of having to modify completed drawings and save money in the process.

To sum up - The Design Team's first functions on letting of the Contract to Build are:

- (a) establish close working relationship with all appropriate employees of the manufacturer;
- (b) endeavour to firm-up and clarify vague areas in the original specification;
- (c) set up agreed system for answering queries;
- (d) advise on any special requirement;
- (e) establish methods of monitoring spending and progress against an agreed programme.

Progressing the Work

Certain components and techniques (particularly Facial Panel Construction - see Appendix 1) are frequently completely strange to the manufacturer. The Design Engineer must either have or acquire sufficient knowledge of the requirements to be able to offer guidance and advice, and must be prepared to resolve any difficulties speedily and in the best interests of all concerned.

As time and construction progresses it is inevitable that changes will be introduced. These may result from more accurate delineation of a previously 'grey' area or even from the need to completely re-design a particular system or area. In all such cases, the Design Engineer will determine whether additional manufacturer's costs will be incurred and, if so, will arrange for the raising of a Change Form. This document (see example in Figure 6) gives outline details of the change and its associated cost. It is the Design Engineer's responsibility to vet the Form, both for accuracy of technical content and reasonableness of cost. Completed Change Forms are submitted for approval to the Authority responsible and, if agreed, the overall costs will be amended.

Obviously, Change Forms can cover omissions as well as additions and hence can sometimes result in a decrease in price. In an ideal world, Change Forms would always be approved before work is put in hand, but as console build progresses so delays become increasingly unacceptable.

The Design Engineer must exercise his discretion as to whether a change is essential and is to be incorporated without delay, leaving the paperwork to follow, or whether it falls into the category of 'nice to have', in which case prior approval will be sought. Naturally, any delay caused by obtaining this approval may have a retrograde effect both on cost and on the possibility of incorporating the change, so that the distinctions between categories of change are often blurred.

Drawings and Documents produced by the manufacturer will be checked by the Design Team and either approved directly, or forwarded for approval. Additionally, assistance will be given in interpreting system operation and preparing the Functional Test Specification that is a requirement for all consoles. Whilst the Design Engineer might have already discussed terminal arrangements with the manufacturer, with a view to providing dummy terminal jigs onboard, he will certainly ensure that accurate details are fed back into the Shipbuilders systems section in order that cable routes can be planned and temporary framework manufactured.

The Design Team act as middle-men between the manufacturer and other interested parties at all times. If necessary, they will negotiate with the manufacturers or suppliers of equipments which will be 'free issued' to the Console manufacturer, to ensure that all information to be passed over can easily be assimilated.

Later in the build phase, contact will be established with the manufacturer's quality control organisation and any local Ministry Stores Procurement representatives. A good understanding of quality standards will aid the initial inspections and the final check following testing, which should be carried out just prior to delivery.

The final comprehensive test takes place when the complete console is available, and represents an important area of work. This functional testing involves taking every circuit in turn, energising it at the appropriate voltage and checking its operation, including the interlocks and interfaces with other systems. Such testing, including the normal point-to-point wiring check, could take many weeks and is carried out using a procedure approved by the Design Team, who would also be represented during the testing.

A thoroughly tested console is essential, since it ensures that all circuits are functionally correct and meet the required specification. It also eliminates expensive onboard modifications by the console manufacturer's engineers, which can delay the ship's Commissioning programme.

If the principle of the liaison, change recording and progress monitoring procedures outlined has been faithfully adhered to, then, notwithstanding the customary frustration and stress associated with 'best laid plans', the result should be a console to the correct standards, fully tested and delivered on schedule.

THE CONTROL OF CHANGES

Origin of Changes

Changes to design are something that must be lived with, since a complex control console evolves through an iterative design process the end product of which has its control fingers reaching into many allied systems. But how can changes be minimised?

A certain number of changes result from new staff working on the project, particularly Naval Staff. Everyone can express a view on a facia arrangement, each having his own personal likes and dislikes, but any such changes proposed at a late stage on a 'nice to have' basis should be instantly rejected. That is not to say that on

occasions such people cannot highlight oversights. It is hoped that the records kept of the early conceptual stages should be sufficient to justify decisions taken and obviate the need for minor improvements in the future.

The majority of changes result from system changes as engineers review the detail of their designs. Again, such changes can be categorised into 'essential' or 'nice to have', although this is not always apparent to the Shipbuilder.

Minimising and Controlling Changes

Certain steps can be taken in an attempt to minimise the number of changes and their effects:

1. Design Freeze Dates should be published as early as possible and all involved must be aware of their importance.
2. During the conceptual design stage, it is essential that all groups of personnel with appropriate knowledge should be consulted and asked to input their thoughts and ideas. Whilst not trying to design by committee, it is essential that the right level of involvement is maintained.
3. The use of a full-size mock-up from the early stages provides an overall 'feel' for the console. It should be continually updated and be available for inspection at any time by all those concerned, including the manufacturer. Mock-ups have been found to be one of the most useful design tools in highlighting errors, limitations and oversights and have often prevented expensive late changes.
4. The evolution of the design must be well-documented so that the reasons why the final arrangement was reached can be seen.
5. The design should be as accommodating as possible to enable essential changes to be implemented with the minimum of disruption.
6. A hard line should be adopted in rejecting non-essential changes; only those proven to be essential should be considered.
7. A good documentation system should be set up to enable changes to be assessed and their effect on cost and programme detailed. This will involve the manufacturer who will also add such clauses as the time period before the 'go ahead' decision must be taken.
8. The required installation date to meet the commissioning programme should be as late as possible. This can be achieved by ensuring the late availability of a shipping route for the console sections. It has the advantage of enabling the Shipbuilder's cables to be terminated in dummy terminal blocks prior to installation. The console design would have to reflect this requirement but it does mean the installation takes place in a clean and virtually completed compartment.

There is obviously no simple solution to dealing with design changes, although approaches as detailed above do help, with a formal change process acting as a brake on those falling in the 'nice to have' category. The education of those involved to appreciate the problems incurred when making non-essential changes probably remains the most effective deterrent.

INSTALLATION AND COMMISSIONING

Activities and Installation Support

The Installation Department and the Drawing Offices should have been collectively involved in the console for some time and, therefore, subject to discussing any last minute hitches, the console will be shipped in the agreed manner and the interface with the ship's systems completed. Any inter-connections provided by the manufacturer between the console sections will already have been advised and installed, and the completed console will have been suitably protected pending commissioning.

The Design Team's work at this stage is by no means complete, particularly with a first-of-class console, since the following areas of activity must now be either started or completed.

- (a) 'Modification Zones' must be established, usually based on each panel (whether facia or internal) thereby allocating a unique pattern number (NATO Stock Number) to each defined area.
- (b) Drawings must be submitted for codification of sections.
- (c) Once pattern numbers have been established, spares requirements (whether onboard, dockyard or main stores holding) can be considered. This work also covers the supply of any special test equipment or tools for replacing new types of component.
- (d) Further discussion can also take place concerning the procurement of complete spare panel sections, which must be built and tested in isolation.
- (e) There is also the need for a maintenance document for the console, to aid ship's staff.
- (f) Further work will be encountered if it is decided to build a simulator.
- (g) The commissioning documentation for the ship will be submitted to the console designer for clarification and vetting of certain areas. This can help to minimise later problems during the commissioning phase.

All the above areas, whilst not the main line activity of design and build, are vital to the overall success of the console project and to its design team who, with their detailed knowledge, are ideally suited to complete the additional tasks.

Commissioning

With the start of commissioning, the Design Team are again involved - providing guidance and assistance. It has been found from experience that any change of design often requires interpretation before it can be accepted - hence any new or unusual features often require long discussions before they are appreciated and accepted.

It has proved essential for any problems encountered during commissioning to be reported back immediately to the Design Team. This enables a full check of the problem to be made, eg was it due to an external fault, a design error or omission, or a misinterpretation of the function, control or reading? Depending on the result of this checking (which could involve original members of the Design Team) the appropriate action will be taken. This could include arranging for the repair or correction of the console, advising a 'ships cabling modification', through the Drawing Office, or the revision of some existing operating procedure which has not been modified or changed to suit the new design.

The arrival of the ship's staff will inevitably give rise to additional questions and queries, since they may be seeing the new console for the first time. It is here that the strength and clarity of the documented records adopted throughout the project is tested in being used to justify the design's logical development. Ship's staff reactions and the suggestions or improvements they raise complete the 'good design cycle' by providing the feedback which is so essential to future designs. On occasions, limitations may also be highlighted which will have to be considered by the Design Team through the change proposal process.

The use of the full size mock-up, which will by now have developed into a cosmetically-accurate dummy console which reflects most of the design changes, is again important during discussions with ships' staff, who may use it to assist in checking their operating procedures and in crew training prior to the availability of a simulator.

Following the completion of the first-of-class console and the updating of documentation, the Design Team's workload will reduce dramatically, although even with repeats for the class there will always be an involvement with minor modifications, faulty components etc, as with any major item of equipment.

CONCLUSIONS

This paper has attempted, albeit in simple terms, to detail a procedure that could be adopted in the overall design and manufacture of a first-of-class machinery control console, although many points made could equally be applied to other consoles and complex items of equipment.

The importance of involving the correct personnel at each stage of the design, followed by further consultation after the sketch designs are produced, has been highlighted. Such involvement should cover all aspects from operational requirements through installation, commissioning and long-term maintenance.

New techniques in construction and the use of the latest available components should be constantly reviewed, offering high potential savings and valid improvements in the final product, witness the recent cited developments in facia construction and illuminated mimic techniques.

Problems in choosing and working with a manufacturer have been considered and the need for a good, open working relationship is an essential requirement. The control of changes that occur during the latter design stages has been dealt with in some detail, and although a method of alleviating the problem has been proposed, there is no easy solution.

The need to maintain comprehensive documentation throughout the project is considered essential in order to control the design evolution and ensure that adequate records are available to all personnel involved during its development and implementation.

All the above items could be considered routine, but are essential considerations if a timely delivery of the console is to be achieved. It is becoming an increasing occurrence at the Shipbuilders Production Meetings to discuss problems associated with the late delivery of the first-of-class Machinery Control Console. Often we find that, having accelerated the final stages of manufacture to meet an installation date, the resultant console is riddled with shortcomings which necessitate expensive onboard working which can ultimately delay the commissioning programme.

There is no all-embracing solution to the problems encountered in designing and manufacturing a complex console, but the need for greater overall control and an awareness of the problems by all those concerned is considered essential. Ideally, one group should take the lead in co-ordinating the project and - assuming that the Shipbuilder has a design capability - then he is uniquely situated to undertake such a role. In the context of supplying consoles for the Royal Navy, it is believed that such an awareness and level of involvement is already being achieved and, whilst not without problems, the standard of product being supplied is becoming increasingly higher as a result.

APPENDIX 1

FACIA PANEL CONSTRUCTION

A search of available literature will show that there is no such thing as a universal technique for designing and constructing Facia Panels. There are many methods of construction, ranging from a simple single sheet of material to complex patented systems of interlocking and replaceable matrix tiles. Similarly, the surface finish can vary from paint or enamel on a metallic sub-surface to anodised aluminium, or to some form of laminate.

After much research, a technique has now been evolved which offers all of the advantages of other established methods with few, if any, of the disadvantages.

The earliest Control Consoles were built in sections by various main subcontractors and assembled by the Shipbuilder. Each used a single sheet of material for the facia, and at least one type had a laminated surface finish. For the first purpose-designed integrated console it was decided to standardise on this latter material.

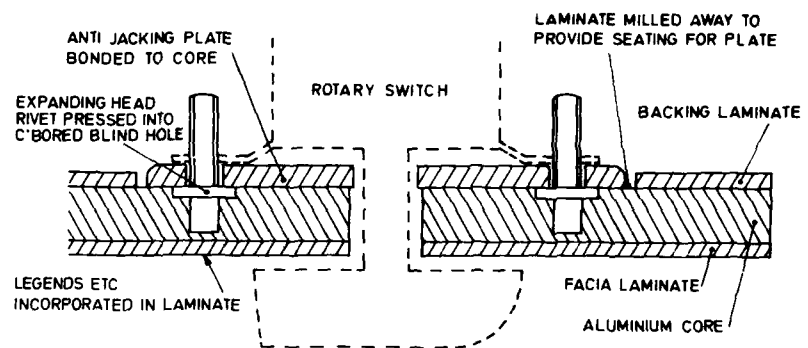
Bonded Laminate/Aluminium Sheet Facia Construction

All Facia and Desk Panels were therefore made of aluminium sheet, to which a melamine laminate was bonded. This covering material is better known as a kitchen work surface, produced under several trade names, and in our case we negotiated with a manufacturer to produce the colours and markings required on a small batch basis, bonded to a hard grade (NS8) aluminium sub-sheet. The finish and wear-resistant qualities of such a surface require no elaboration and the Panels were aesthetically excellent.

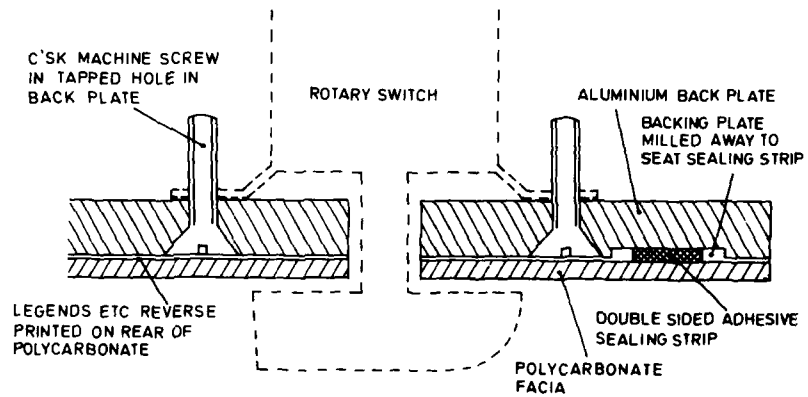
Some difficulties arose during production. The brittle nature of the laminate made machining less than easy if chips were to be avoided around edges; and high tool speeds meant that frequent sharpening of cutters was required. Laminate is hygroscopic and expands in humid conditions, hence a balancing layer of laminate had to be bonded to the rear surface of the aluminium to avoid bowing. (This presents a problem when using laminate Facias for Mimics - see Appendix 2).

A completed Panel had a fully finished surface, therefore extra care was required during subsequent operations to prevent damage, and component fixings such as those required for rotary switches etc could not be allowed to penetrate the surface. After discussion, a blind rivet type fixing was used to provide such studs. To avoid the 'jacking out' effect created when tightening fixing nuts, a special 'anti-jacking' plate was fitted at each stud position (see Figure 7(a)).

All in all, the mechanical preparation of the Facia Panels could not be described as simple. Fortunately, such problems had been foreseen and a 'machining contingency' set of panels had also been



(a) Laminate Type Facia Panel



(b) Polycarbonate Type Facia Panel

Figure 7 Switch Fixing Methods on Laminate and Polycarbonate Facia Panels
K2-30

ordered. After the production completion of the first four consoles, several of these 'contingency' panels had in fact been used to replace damaged units.

The principal disadvantage of laminate as a facia material became obvious as console building progressed. Because of the specialised nature of the design and manufacture of the Facias, orders had to be placed at an early stage. (The Paper to which this Appendix relates demonstrates how changes in design affect console build, and how such changes often appear at a late stage.) It rapidly became apparent that many changes can have a deleterious effect on console Facias, and the difficulty of modifying an already constructed panel became of paramount importance.

It must be borne in mind that legends, titles and flow lines form part of the laminate 'pattern' and are actually in the sub-surface of the laminate, covered by a wear-resistant transparent surface layer; hence modifications to any existing symbol or legend becomes almost impossible. Even machining an additional component hole in an assembled panel is a major undertaking, since due to the machining difficulties mentioned earlier, the Panel has to be completely stripped down. Eventually it had to be accepted that the only way to satisfactorily modify a flow line or legend was to affix a specially printed aluminium foil overlay, with background colour as near as possible to the original, and bearing the corrected symbols. Indeed, the first laminate facia console has the appearance of a much-travelled suitcase.

Review of Facia Construction

Fresh consideration was given to the type of Panel to be used for future consoles, and again much research and experimentation was put in hand. Interlocking tiles were rejected because, although interchangeable, the matrix support structure made their use on an opening Desk or Facia Panel impracticable. Furthermore, it was felt that the finished surface with joints visible every few inches would not meet drip-proof requirements and its appearance left a lot to be desired. Single-sheet construction was preferred and, although painting or anodising a metal sheet would be much cheaper than the laminate finish, the same difficulties in incorporating modifications still applied.

Finally, with the assistance of a specialised firm of sub-contractors - Messrs Carville Ltd, an alternative was developed.

Polycarbonate Facia Construction

The basic Panel consists of an aluminium sheet, machined as required for components, and with fixing studs consisting of counter-sunk head machine screws inserted from the front face. The need for expensive and complicated blind rivet fixings has been dispensed with. The surface finish consists of a 2mm thick sheet of transparent polycarbonate with the flowlines and legends etc silk-screened onto the rear face and a mar-resistant anti-glare finish applied to the front face. The polycarbonate is secured to the outer edges of the aluminium backing panel by a double-sided adhesive tape which provides a drip-proof seal, permits subsequent removal, and allows for differential expansion between the polycarbonate and aluminium (see Figure 7(b)).

It is appreciated that the polycarbonate is perhaps not as wear-resistant as the laminate surface, but its ease of machining and the clean, unbroken anti-glare finish gives an appearance at least equal to laminate and (in the case of illuminated mimics) far superior. The main advantage, apart from lower capital cost, lies in the ability to carry out modifications without scrapping a major portion of a completed console.

It must be pointed out that silk-screening is not a precision process. Therefore, to ensure that all components fit in their 'visually correct' positions in relation to flow lines and legends etc, Carville have developed a technique of using the printed polycarbonate overlay to establish component machining positions both in the overlay and in the backing panel. Obviously it is still necessary to produce the actual facia design at a relatively early stage of console production. However, the facia finish is not fitted until the time comes for the components to be installed, and it can be adequately protected until that time. Any modifications such as legend changes can be carried out by removing the background colour and the obsolete legend from the overlay, substituting the new legend and repainting the background. Additional holes for extra components can be handled just as easily and, even where components are to be removed, the only item to be scrapped is the overlay, since the redundant hole can be left in the aluminium sheet without being seen.

After panel assembly, changes are a little more difficult to accommodate since components will generally have to be removed to enable the polycarbonate to be freed; but from this point on, the modification procedure is largely as before, with the worst case incurring only the relatively cheap replacement overlay. Even major changes have been found to be acceptable since, with a little more work, the completed backing panel can have the faulty section machined away and a fresh piece of aluminium dovetailed in to accept the new components.

The resistance of polycarbonate to damage from impact is well-proven and, by the choice of a suitable manufacturer and grade of material, all MOD(N) requirements for flammability, smoke emission and non-toxicity can be met. The final product is robust and attractive, and is much cheaper than its earlier counterpart. Above all, it can easily be modified as and when the need arises.

It is felt that this new technique adequately meets the control console designer, builder and users' criteria, and currently offers the optimum solution to the problem of how to construct facia panels subject to modification and what materials to use.

APPENDIX 2

ILLUMINATED MIMIC SYSTEMS

It is readily agreed that in any complex plant control system the use of a mimic layout is invaluable in speeding operator training and in avoiding operational errors. A further gain is evidenced if the mimic system can be illuminated, since the flowline itself can indicate the state of a system parameter: lit for 'On', extinguished for 'Off'. Further advantages will arise by arranging for the outline-say around a particular plant shape - to flash under predetermined fault conditions, thus drawing the operator's attention to the area in question and avoiding delay in critical situations. This Appendix gives details of work already undertaken in the design and build of such a system.

Evaluation of Illuminated Mimic Methods

At the start of the design stage for the first fully integrated console, an in-depth evaluation was carried out into all available methods for producing illuminated mimics. Amongst those methods examined were the following:

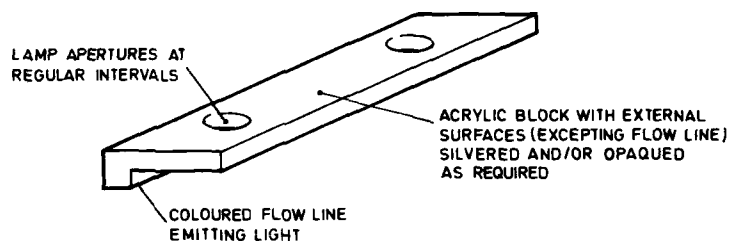
- (a) Lamps inset into the flowline (bulbs replaceable from the front).
- (b) Lamps inset into the flowline (bulbs replaceable from the rear).
- (c) Electroluminescent Panels.
- (d) Edge-illuminated flowlines.
- (e) Fibre Optic Systems.
- (f) Inset Light Emitting Diodes (LED's).

Method (a) provided good brightness but was rejected because of the intrusion of the lampholder onto the Panel front and the blank section of flowline covered by the holder.

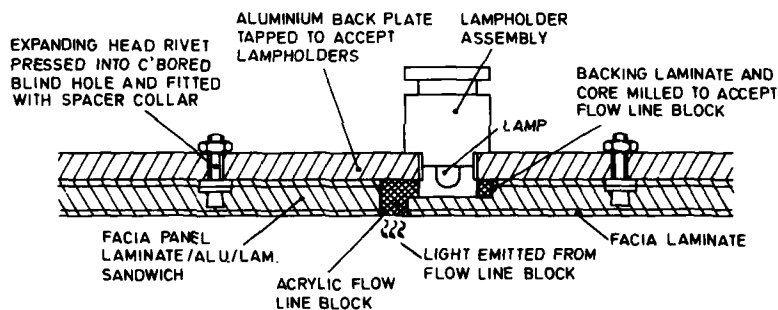
Method (b) had no visible lampholder, but was not acceptable because of the bright patch effect arising from direct viewing of the lamps.

Method (c) required excessively high voltages for adequate illumination in normal ambient lighting, had a limited range of colours and generally incorporated fragile glass sheets in its construction.

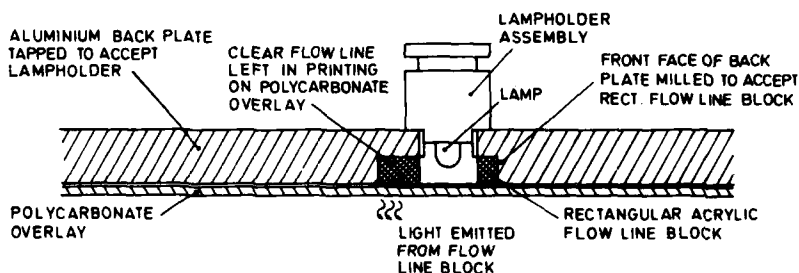
Method (d) was the traditional system of illuminating flowlines - an acrylic slab the same thickness as the flowlines mounted at right angles to the face of the Panel, and with lamps inset into the rear edge of the slab. Evenness of illumination was good, with the light being diffused through about 100mm of acrylic, but the rear projection of the slab interfered with component mounting to an unacceptable extent.



(a) Typical Flow Line Block (for laminate facias)



(b) Illuminated Laminate Facia



(c) Illuminated Polycarbonate Facia

Figure 8 Illuminated Facia Panel Details

Method (e) used fibre optics, either buried lengthwise in the facia and having their surface specially treated to allow the light passing through to 'leak', or having their ends inserted directly into the rear of the flowline. This was rejected because of the patchy effect 'like a striped caterpillar or dotted line.'

Method (f) was also rejected due to an insufficient choice of colours and the excessive wiring required for multiple LED's installed on a reasonably long flowline.

Original Illuminated Mimic Console Development

Eventually, the decision was made to adopt a compromise between Methods (a) and (d). The lamps would be rear-mounted but offset from the flowline to give an edge-lit effect. However, instead of the flowline protruding from the back of the panel, it would be contained within the structure of the facia. A typical flowline block is shown in Figure 8(a) and its incorporation into a laminate-type Facia Panel in Figure 8(b).

As the first illuminated mimic panel was built and tested the usual problems arose. Some components - notably rotary switches, appear very small when mounted on the facia, and require the flowlines to be terminated close to their shafts. The space occupied on the rear of the Panel, however, precludes the lampholder from being mounted in its most effective position, and some compromise must be made. Existing lampholders were thought to be unsuitable since they required tools for lamp renewal or contained loose parts, either of which could easily be dropped across adjacent live terminals. A special lampholder had to be designed and developed; but in order to be able to change lamps, removal space had to be allowed around each holder, which again interfered with the optimum mounting positions.

As testing progressed, further problems were encountered. Each lamp was totally enclosed within the facia panel and, due to the laminate type of facia construction existing at that time, the heat build-up was considerable. In order to prevent premature filament failure the lamps were under-run, but the drop in voltage and hence light output was accompanied by a reduction in colour temperature; this led to difficulties in producing certain flowline colours at the blue end of the spectrum.

Specially released batches of lamps were specified but it was found that there was still considerable variation in their light output quality and it was considered that problems could occur in the future when replacements were needed. Another review was carried out culminating in the consensus of opinion that, in order to produce an absolutely even flowline, a certain amount of individual 'tuning' is required to cater for different shapes of flowline block, differing lamp-spacings etc.

It would be perfectly correct to say that, although the first control console to incorporate illuminated mimics was excellent from an operator point of view, it could prove troublesome to the maintainer. The incorporation of 400 individual lamps inevitably reduced the overall MTBF, and some of these could not be replaced without opening facias and desk panels and interfering with normal operations. Although this system was considered to be the only acceptable method currently available, further research was obviously needed.

Simultaneously, two events took place which were to result in realisation of the optimum control console design technique proposed in this paper. On the facia design front, development using polycarbonate material began, whilst on the illuminated mimic front, discussions got underway with Messrs Carville Ltd who had now perfected the necessary light tuning skills required to make the original system workable.

Transition from Lamps to Fibre Optic Illumination

It was decided at this stage that a way must be found of getting indicator lamps away from the facia panel material in order to avoid localised excessive heat build-up and to facilitate lamp-changing.

Fibre optic light guides had already been investigated and rejected because of the high brightness of the end when directly viewed. However, the design team were only too aware of the inherent reliability benefits of a fibre-optic-based system and it was suggested that special lens ends might be designed and fitted which would give the same polar curve as the existing lamp. The fibres might then be a direct replacement for the lampholders. It was also realised that, instead of a multiplicity of lamps, it would be more efficient to use a single lamp feeding all fibres. If some form of shutter could be provided for each fibre, then it would be possible to have the lamp burning continuously to extend its life, and switch each fibre or group of fibres on or off as required to illuminate the flowlines.

Fibre Optic/LCD Illuminated Mimic Console

The final system which, at the time of writing, is being tested to ensure compliance with Ministry of Defence shock and vibration requirements, and which is the subject of a patent application, consists of a standard 3U rack mounted at the rear of the console. The rack contains up to three 24E modules each of which holds a tungsten halogen low-voltage lamp fitted with dichroic reflector. Light from the lamp passes to a collector assembly containing a heat filter and collimator lens whence it passes through a bundle of 72 fibre optic cables and terminates at the input face of a special Liquid Crystal Device (LCD) (see Figure 9).

The LCD has been specially developed and is arranged in a matrix form of 12 x 6 separately addressed pads. When the module is fitted into the rack, precision dowelling ensures that light passing through any section of the LCD is fed into one of 72 output fibres mounted at the rear of the rack. The LCD is arranged to be energised to clear and is of the cholesteric nematic type, driven by a low voltage AC supply. The Tungsten Halogen lamp burns continuously, has an estimated life of around 6,000 hours and has a high colour temperature, making all flowline colours easier to obtain. Since the rack is mounted at the rear of the console, ventilation is easier to provide, and, with the restrictions on lamp wall temperature that are common to all quartz envelope lamps, normal convection cooling is adequate. Lamp replacement is effected immediately by replacing the module with a ready-use spare. Since this also automatically replaces the LCD at the same time, the two most delicate components are easily maintained (see Figure 10).

One of the 72 fibres from each module is brought to a convenient position on the appropriate facia and arranged for direct viewing

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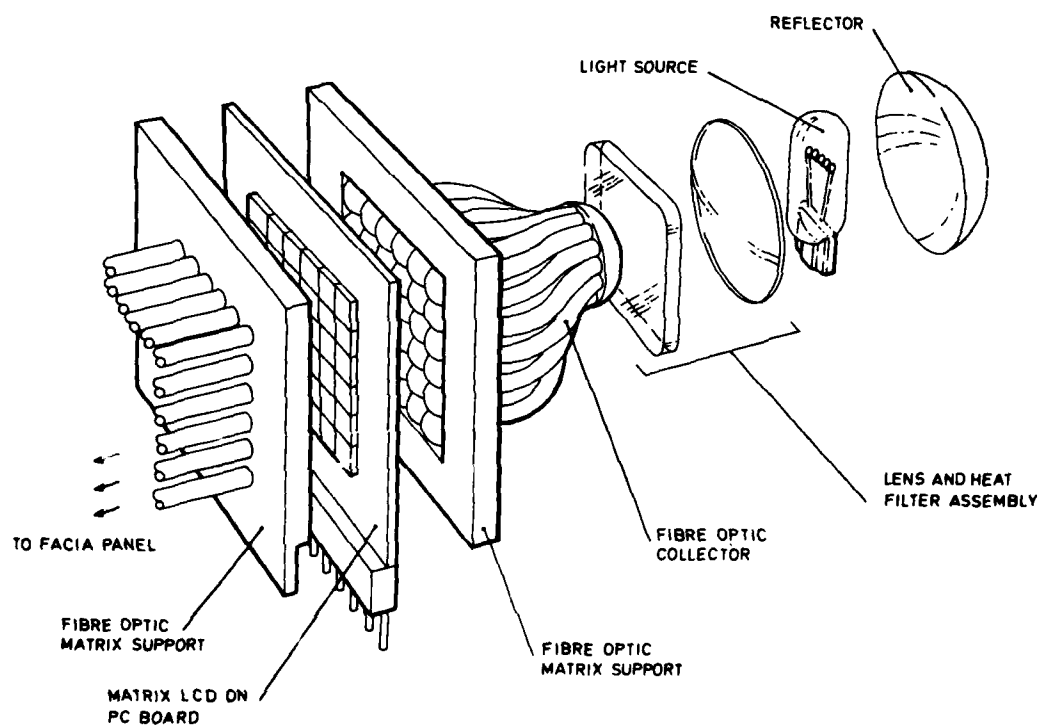


Figure 9 General Arrangement of Fibre Optic Illuminated Mimic System

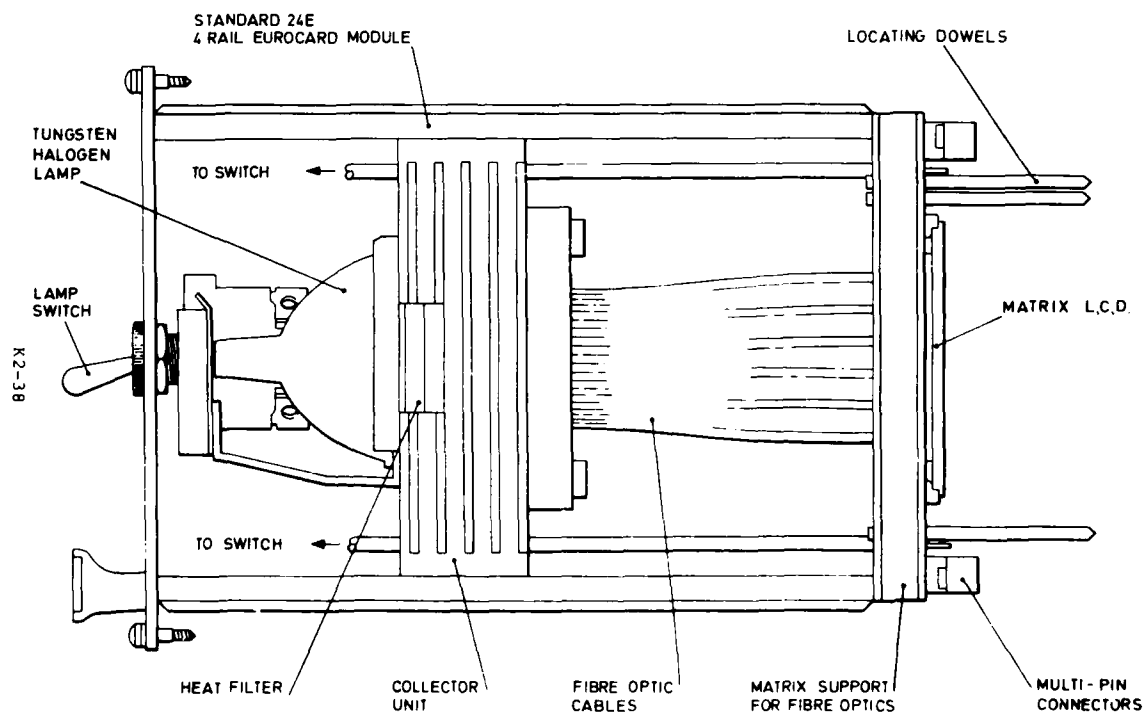


Figure 10 Fibre Optic Light Output Unit

with a special diffusing lens. The resulting indicators are labelled 'Lamp No.1', 'Lamp No.2' etc, and act as immediate tell-tales for the operator in the event of failure.

The 72 fibres that can be driven by each module are brought to the rear of the console facia panel, where a specially designed lens end is fitted into existing lampholder holes. Thus the new system is compatible with existing lamps at the facia panel interface.

For those flowlines whose continuous reliability is essential, two separate light box modules would be mounted in one rack, and the length of flowline fed alternately from either source. Thus failure of one lamp or LCD would only half extinguish the flowline allowing operations to proceed normally until replacement was effected (see Figure 11).

In the event of such a flowline being either too short, or so positioned as to be unable to accept more than one light input position, a technique has been developed for incorporating two fibres into a single lens, thus permitting the same chance of operating on half light while the other module is replaced.

Latest Developments

The adoption of the newly developed polycarbonate facia construction technique (detailed in Appendix 1) has now permitted the simplification of flowline construction at the facia panel and has led to the adoption of flowline shapes that can be readily replaced (compare Figure 8(b) with (c)). An additional benefit of the technique is that the colour of flowlines can now be modified as well as their positions. The specially developed LCD's can also be arranged to pass coloured light, so that the possibility of a flowline actually changing colour to indicate alternative parameters is offered, eg 'Out' for stationary shaft; 'Lit green' for forward rotation; 'Lit red' for astern rotation.

Finally, it is worth pointing out that the very low current drain of LCD's (in our case approximately 5 μ A per pad) renders them ideally suited to direct interfacing with solid state logic. Since the largest illuminated facia panels yet constructed require no more than around 120 lampholders/light input points, one standard 3U rack will cope with both of the modules for such a panel and still have sufficient space for card-mounted logic drives, power supplies etc. Furthermore, the inside of the console is freed of the dozens of relays hitherto necessary to provide the high current drive associated with over 100 watts of lamp load.

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EXPERIENCE WITH DIRECT MEASUREMENT OF
STEERING GENERATED PROPULSION LOSSES.

by

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ABSTRACT

The paper presents the results from five years of experience with direct measurement of propulsion losses related to autopilot and steering gear performance. More than ten ships of different types have been involved in this effort.

The paper shows how it has been possible to obtain statistical significant values of steering generated losses when different control equipments are installed. Measurement of very small fractions of speed and shaft power is shown to be possible, without using excessive periods of time for the experiments. Dedicated computing and motion monitoring equipment supplemented by ship installed instrumentation makes this possible.

Important results presented are values of speed and power consumption obtained when different autopilots and steering gears are used. Measured values of propulsion losses are further discussed in the paper referring to different steering devices. Extensive series of short time experiments, and results obtained over extended periods, show the principles of control equipment which should be used for achieving minimal values of steering generated losses. Among the possibilities, the analog steering gear is found to offer the greatest average improvement and selftuning autopilots based on a Kalman filter approach are significantly superior to conventional controllers in rough weather.

INTRODUCTION

More than a decade ago, Nomoto, Norrbin and others found that ship propulsion losses were closely related to the performance of the ships steering equipment. The relation found was simple, the better the equipment, the smaller the propulsion losses. Due to technology, the steering equipment at that time was constructed with little consideration to the finer aspects of control theory. Many autopilots as example were of simple proportional-integral (PI) type. And all steering gear remote control systems were of the three state (Bang-bang) type. As a result rather stable limit cycling was commonly encountered in autopilot steering systems. Due to the action of the autopilots integrator the average course was correct, and most navigators were satisfied by this fact.

Ship speed, however, dropped slightly in the continued zig-zag manoeuvre, which was forced upon the vessel by the early autopilot equipment. On most ships the limit cycle, which was introduced by the steering equipment itself, had magnitudes of rudder angle from 3 to 10

degrees, even in fine weather.

During the past five years, considerable effort has been devoted to the development of better performing steering equipment which does not suffer from introducing extraneous speed losses. In order to achieve this, new control methods have been introduced in steering gear servo loops and in autopilots.

Among the most promising results can be mentioned analog control of the steering gear and adaptive control in the autopilot controller.

When introducing such new equipment, assessment of the magnitude of possible improvements in propulsion efficiency and economy is of the utmost importance.

Based on a range of sea trials with the purpose of evaluating the performance of different automatic steering systems, this problem is addressed in the paper.

Specific attention is given to the measurement of the changes in speed and fuel consumption associated with using different types of control equipment. Conclusive sea trial results are further presented. They show how direct measurement of speed loss is indeed possible, and how these results clearly indicate the types of control equipment which should be preferred.

The paper is separated in three main sections.

First, elements of the fundamental ship speed and propulsion characteristics are reviewed, and the properties of external disturbances and the influence of shallow water effects on ship resistance are discussed. Based on this an experimental procedure for measuring the tiny propulsion losses is outlined. Propulsion losses are then related to different categories of steering equipment. Principal schematics show the installations actually tested. The last section presents major results from extensive series of sea trials.

ELEMENTS OF SHIP RESISTANCE AND PROPULSION DYNAMICS

Ship speed

The towing force necessary for ship propulsion at a certain speed may be considered to be mainly the effect of hull friction although wave generation further increases the resistance at high speeds. In a deep sea condition the resistance approximately increases with the square of ship speed. Hence with m being ship mass, X_{rr} the resistance coefficient, T_{loss} the excess drag force, and $(1-t)T$ a thrust deduction factor, the principal ship speed equation is

$$mU = X_{rr}U^2 + (1-t)T + T_{loss} \quad (1)$$

Excess drag force is due to hull motions, steering activity, waves, and wind:

$$T_{loss} = (m - X_{vr})vr + X_{st} \dot{\delta} + T_{wave} + T_{wind} \quad (2)$$

The first loss term is proportional to v_r , sway velocity and rate of turn of the vessel. This product appears as a consequence of the ship being an object to both translations and rotations. The acceleration about the center of gravity is

$$\frac{\partial^2 x}{\partial t^2} - v_r \quad (3)$$

where the second derivative of x is the acceleration in ship fixed coordinates. The term v_r is a fictive acceleration of the ship. It gives a drag force due to hull motions of amount

$$(m - X_{v_r}) v_r \quad (4)$$

The total mass associated with accelerations of the vessel is not the mass of the hull displacement only, a certain "apparent mass" must be added to this. In the case of the v_r acceleration, the added mass is X_{v_r} , which has negative sign and is approximately -0.6 m for VLCC's in ballast, and -0.8 m in fully loaded condition.

The second contribution to the excess drag force is the rudder surge force $X_{\delta\delta} \delta^2$.

The performance of the rudder may be determined from considering the rudder as a fin with small aspect ratio, i.e. a small ratio between height and chord. According to hydrodynamic theory the rudder force may be expressed by (Comstock 1967)

$$X_{\delta\delta} \delta^2 = \frac{\rho}{2} \bar{C}^2 \frac{h}{\pi(h/c)} \left(\frac{2\pi}{1+2c/h} \right)^2 \delta^2 \quad (5)$$

where \bar{C}^2 is the square of average flow past the rudder. This flow was expressed by Berlekom (1975) as

$$\bar{C}^2 = U^2 (1 - w_0)^2 + \frac{8\alpha\beta}{\pi\rho D h} T \quad (6)$$

where α is the ratio between propeller diameter and height of rudder. β is a correction factor which accounts for the spacing between rudder stock and propeller. A common value of β is 0.8. The factor $(1 - w_0)$ is the wake fraction which expresses the average reduction of flow velocity in the propeller disc compared to ship speed.

The propeller thrust T may be related to ship speed by the equivalence between ship resistance and developed propeller thrust. For the ship at steady speed we have balance between thrust and hull resistance

$$R(U) = (1-t)T = -X_{uu} U^2 \quad (7)$$

The factor $(1-t)$ is the thrust deduction. The approximation of the resistance curve by the U^2 term is only valid when wavemaking of the hull may be neglected. The coefficients X_{uu} , $(1-t)$, and $(1-w_0)$ are essentially constant over the speed range considered for a sea trial aiming propulsion loss measurement, but they should be changed according to the actual loading condition.

The rudder drag force is consequently

$$X_{\delta\delta} \delta^2 = \frac{\rho}{2} \frac{C^2}{\pi} \left(\frac{2}{1+2C/h} \right)^2 ((1-w_\delta)^2 - \frac{8a\beta X_{uu}}{(1-t)\pi\rho Dh}) U^2 \delta^2 \quad (8)$$

Note that rudder drag increases by the square of the rudder angle and for a fixed angle also by ship speed squared.

The expressions (4) and (8) given above show the drag force due to hull motions and rudder deflection. They are predictable and accessible provided measurements of r , v and δ are available.

Propeller performance

The propeller action in a field of steady inflow is described by relations between developed thrust T , shaft torque Q , and velocity components of the flow. By using momentum theory and considering the lift developed by the blades, thrust and torque can be shown to depend on bilinear and quadratic terms in shaft speed n and inflow velocity V_A . During periods of steady course keeping, fluctuations in propeller load are not excessive compared with average load. From practical experience the propeller thrust and torque can then be readily assessed.

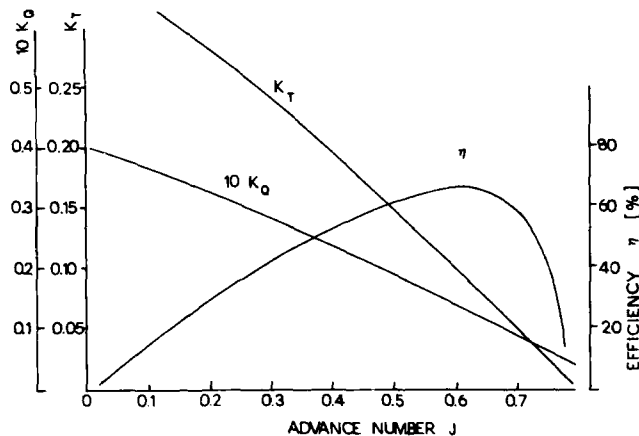


Figure 1. Open water propeller characteristics.

Propeller performance is commonly presented in nondimensional form by the torque and thrust coefficients K_Q and K_T . Their variation over the range of propeller loads are plotted in figure 2 where J is the advance number. For the moderate load variations considered, K_Q and K_T can be expressed satisfactorily accurately by a linear approximation.

In dimensional form this gives

$$\begin{aligned} T &= T_{nn} n^2 + T_{nv} n V_A \\ Q &= Q_{nn} n^2 + Q_{nv} n V_A \\ V_A &= (1-w_o)U \end{aligned} \quad (9)$$

These equations show the ship speed and propeller revolutions to be closely related. Therefore shaft speed and fuel consumption will change when the ship is exposed to excess drag force.

An analysis of these effects is based on the entire ship speed and propulsion system. It is sketched in figure 2.

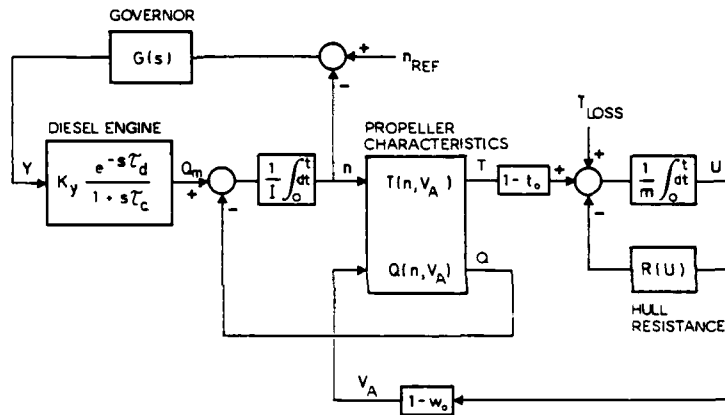


Figure 2. Ship speed and propulsion system schematics.

The nonlinear ship speed equation also provides the effective timeconstant for minor changes in ship speed. The value of the timeconstant is found to be (Blanke (1978))

$$\tau_s = \frac{m}{\frac{\partial R(u)}{\partial U} - (1-t) T_{nv} n_o (1-w_o)} \quad (10)$$

As an approximation

$$\tau_s \approx 0.5 \frac{m}{-2X_{uu} U}$$

Change in speed and power from excess drag force

As a result of a closer scrutiny of the effects of applying an excess drag force T_{loss} to a ship, given the set point n_{ref} for shaft speed, it was shown (Blanke (1980)) how ship speed and shaft power are functions of the gain in the closed loop that controls shaft speed. These relations are plotted in figure 3.

Although these values were obtained for a diesel engine prime mover, they are equally valid for other propulsion systems, eg. turbine driven ships, because the result is expressed in terms of loop gain in the RPM regulation loop. This is independent of how the gain physically is obtained.

The extremes in figure 3 are of specific practical importance. Using a governor with very high static gain, 1% drag force is converted to 0.3% speed loss and 0.5% excess power.

If constant shaft power is maintained, such as approached with steam turbine propulsion, the speed loss is 0.48%.

If operating a diesel engine at constant fuel index, a constant shaft torque results which is equivalent to zero open loop gain in figure 3. In this condition, a power decrease of 0.25% is achieved and associated with 0.56% reduced speed.

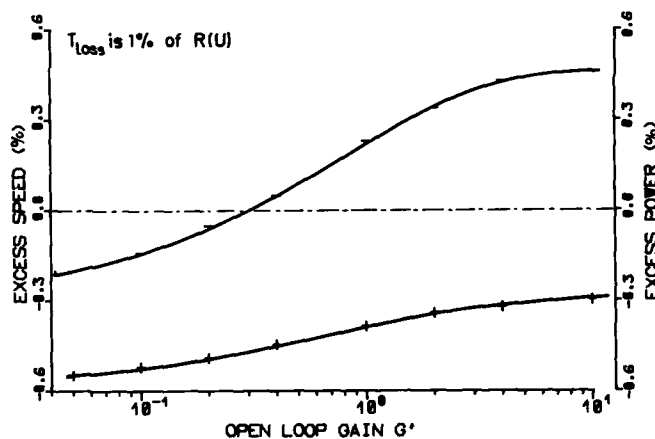


Figure 3. Excess speed and power due to a static drag force of amount 1% of ship resistance. Simulation results for container ship at 23 knots.

When measuring propulsion losses, it is mandatory therefore, that both shaft power and ship speed are monitored. If only ship speed is used for expressing steering efficiency, the associated power consumption is entirely depending upon the type of shaft speed control being used and on the actual condition of the equipment.

Regarding voyage economy, it is not necessarily optimal to use minimum fuel per nautical mile sailed, because voyage time and other commercial factors are also of importance. However, the steering system and autopilot may be evaluated from its ability to obtain

increased speed at constant power, compared with other equipments.

Shallow water

The assessment of added resistance is extremely sensitive to shallow water effects. The increase in ship resistance in shallow water is illustrated in figure 4 where resistance characteristics for a 340000 tdw VLCC tanker and a 24000 tdw container ship are plotted. The parameter on the curves is the ratio between water depth and the square root of ship draught times its breadth. The shallow water resistance data were taken from Comstock (1967) which again is based on Schlichtings work. These data have proven to be rather accurate.

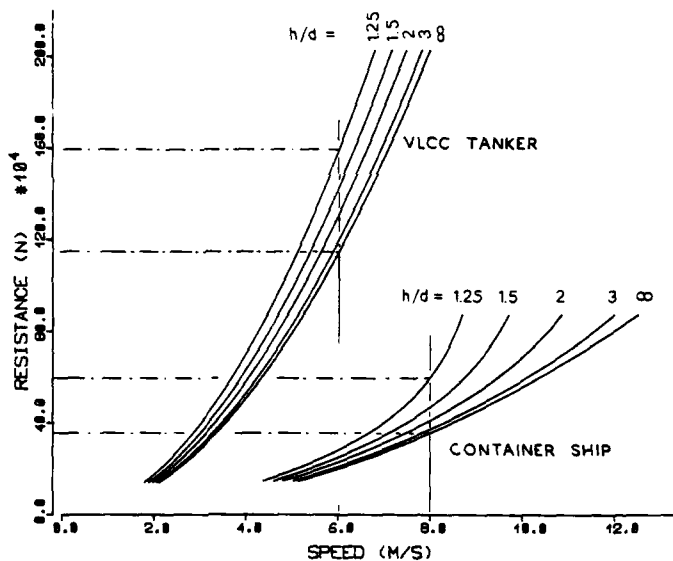


Figure 4. Resistance characteristics in shallow water

The 2% limit for change in resistance is found to be $h=98$ m for the tanker, and $h=44$ m for the container ship, both at full load.

Measurements of added resistance due to steering should therefore not be carried out unless water depth is some ten times the draught of the ship.

In addition to increased resistance in shallow water, the steering quality of the ship is changed. Over a certain range of water depths, a destabilizing effect occurs. This was experimentally demonstrated by Fujino (1976), and test trials on board a VLCC tanker

demonstrated steering instability with an otherwise well tuned autopilot. Recordings are shown in figure

External disturbances

The external disturbances from wind and waves can easily contribute 10% to the hull resistance. As they are random by nature, assessment of steering quality in terms of added resistance becomes quite difficult and in order to obtain results with reasonably little scatter, experiments have to be conducted with due regard to the nature of the disturbances.

Ship response to wind is the composite effect of the action of two separable parts of air flow. One is regarded as the mean wind, which exposes the ship to steady forces over periods much longer than the timeconstant of ship speed dynamics, 50-500 seconds. The second component is caused by the turbulence in the air associated with the average mass flow in the mean wind. The amount of turbulence increases with increased average wind speed.

The spectrum of wind is plotted in figure 5. The bulk of turbulent energy is shifted towards higher frequencies with increasing values of the average wind. The figure also shows the spectrum of the average wind to have a peak equivalent to a four days period.

The components of average wind and the turbulent part are seen to be clearly separated by the spectral gap between 15 minutes and 1.5 hours. The existence of this gap allows for the distinction between average and turbulent wind components.

Due to the spectral gap, the most feasible averaging period when measuring propulsion performance is 30 to 60 minutes.

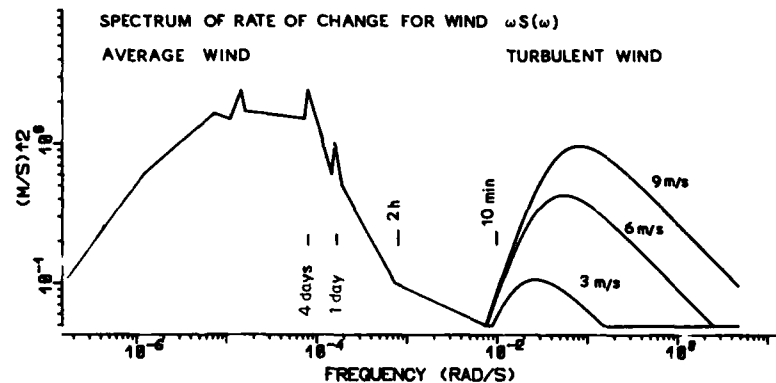


Figure 5. Idealization of the wind speed spectrum. The spectrum of average wind is adapted from Davenport (1978).

When comparing different equipments onboard by selecting one or another, a measurement period of 30 minutes is feasible. If longer, too much change in average wind will make a direct comparison of performance difficult, but rather long sequences of measurements are necessary for obtaining statistical significant results.

The force exerted by wind is a function of the square of wind speed V_{rel} relative to the ship, and also of the angle of attack from wind χ .

$$X_{wind} = \frac{1}{2} \rho_a A_x C_x(\chi) V_{rel}^2 \quad (11)$$

where ρ_a is the mass density of air, A_x is a cross section area, and $C_x(\chi)$ is a wind force coefficient that is obtainable from data given in the literature for quite a few types of ships (Aage (1971), Berlekom, Trägårdh and Dellhag (1975)).

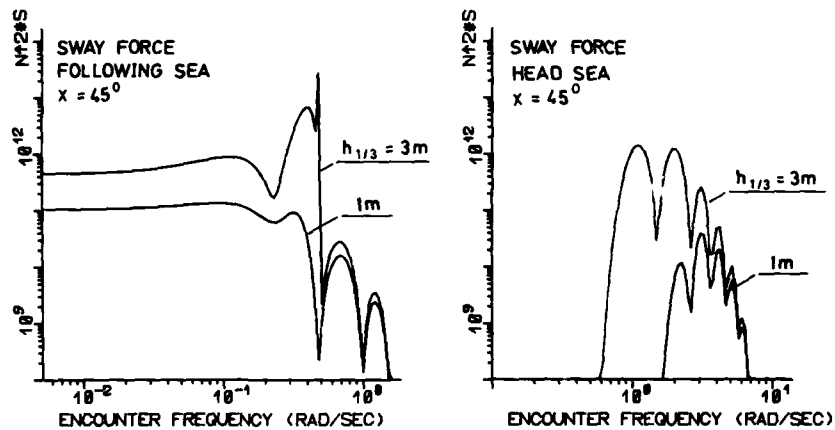


Figure 6. Sway force spectrum for quartering head and following sea. Ship speed is 23 knots.

Wave forces are mainly due to the force associated with the wave height, but the resistance in waves increase by the square of wave elevation. The spectrum of resistance in waves will therefore be convolutions of similar spectras, and will have a uniform amplitude up to periods of 10-50 seconds. Hence wave resistance is comparable to a white noise disturbance, and long averaging periods give the least variance.

As the sea state varies approximately as the average wind, averaging periods of 30 minutes are also feasible when regarding wave disturbances.

EXPERIMENT PROCEDURE

Based on the previous observations, the following procedure evolves for measurement of propulsion losses:

1. If possible only two competing steering principles should be tested simultaneously. The installation should allow for immediate and bumpless switching from one system to another.
2. Test trials should be planned as a series of 20-40 minute tests.
3. Test runs are preferably made as a consecutive series of tests with change of system after each run.
4. More than five times τ should be allowed after each change of equipment in order to let ship speed settle
5. Statistical significant results are only obtained if at least 10-20 test runs are conducted with each equipment. In bad weather this number should be increased.

Monitoring of average values over about 30 min is only possible by using computing equipment that performs integration of the signals of interest over the entire period. Ordinary low pass filtering techniques will not provide results which are accurate to within fractions of a percent. This accuracy is indispensable for such experiments.

The signals monitored in a major part of the experiments are the following:

- $\Delta\psi$ difference between the actual course and the course setting on the autopilot repeater.
- r rate of turn from rate gyro. Readout is not quantized. Resolution is 0.001 deg/s.
- δ rudder angle from potentiometer connected to rudder stock.
- n propeller revolutions from ship installed tachometer.
- u ship speed obtained from the ship's LOG.
- Q_m shaft torque developed by the engine. Either directly measured or, on diesel engines, indirectly as the fuel pump index.
- P shaft power. Obtained by multiplying instantaneous values of n by Q_m .

The above listed signals are all available as voltages. Signal processing is performed by the EMRI "SPICE" portable computer unit.

PROPULSION LOSSES RELATED TO STEERING EQUIPMENT

The important elements in the control loop

The exact propulsion efficiency as related to the steering control system depends upon all involved elements and upon the environment, i.e. the weather and seastate. Starting with the ship, the important elements of the equipment involved are:

1. Ship's static steering characteristics:
 - a. Stable
 - b. Unstable
2. Ship's dynamic steering characteristics:
 - a. Sensitive to the rudder
 - b. Insensitive to the rudder
3. Rudder speed (Steering gear hard over time):
 - a. Slow
 - b. Matched to length/speed ratio of the ship
 - c. Fast
4. Steering gear control law:
 - a. Analog (Continuous control)
 - b. Bang-bang (Three state control)
5. Autopilot control law:
 - a. Conventional PID type
 - b. Adaptive, possibly with Kalman filtering

One of the combinations, and unstable ship with low sensitivity to the rudder and equipped with a slow steering gear, would probably be stopped during the test seatrials as unsteerable. Otherwise control equipment designers take 1. and 2. for given, and influence steering performance through their selections in 4. and 5. The rudder speed is normally given by the requirements of the owner, and the classification society. Thereby big, slow ships get fast steering gears and small, fast ships will be equipped with slow steering gears. This affects both the steering ability of the ship and the steering generated propulsion losses. Steering gear specifications should therefore be made with due consideration to possible requirements of the course control system.

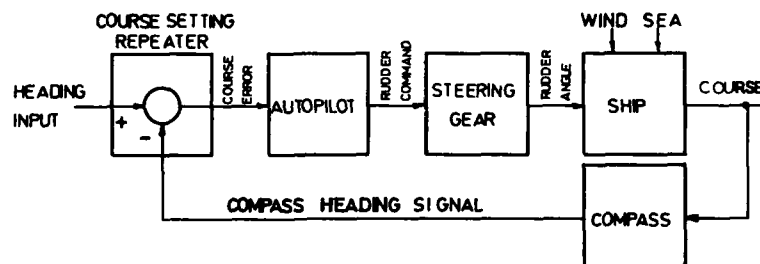


Figure 7. Course control loop.
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Discussion of typical equipment

From the very start of the investigations in 1974, it turned out, that the steering gear remote control system was the part of the course control loop which most significantly contributed to propulsion losses in calm weather. It appeared that improvements in the rudder servo loop could be visualized directly and that an increase in propulsion efficiency could be proven through measurements. This fact has not been widely recognized.

The investigations have included several different autopilot designs, of which some were adaptive or self tuning. Results of the test trials show a wide scatter in steering quality of autopilots, and superior performance of the advanced controller designs have mainly been found in rough weather conditions. Principles of autopilot design have been thoroughly discussed in the literature, whereas steering gear control concepts have been devoted much less attention. The following subsections therefore describe principles of typically applied steering gear control equipment in some detail.

The steering gear control system

By tradition, very few steering gear manufacturers have supplied the complete rudder servo system. In most cases the loop has been closed by a rudder servo, supplied by autopilot manufacturers. The steering gear supply stopped at the valves or at the telemotor. Nevertheless the only reasonable place to separate an autopilot and a steering gear system is at the rudder order level. A steering gear is a device that converts rudder order (in degrees) to rudder angle (in degrees).

Analog control in the steering gear is defined as the method, that moves the rudder with a speed that is proportional to the error in the servo loop, unless this error has exceeded the proportional band, in which case full stroke of the pump(s) has been reached.

Bang-bang control in the steering gear is defined as the method, where one or more servo loops have discrete levels:

1. Full speed order to PORT, or to STBD
2. Zero speed order (within the deadband)

The deadband or insensitivity zone is measured in degrees of servo error.

Figure 7 shows the autopilot control loop elements and figure 8 shows the two control methods together with their responses to the same pseudorandom signal.

Single loop systems are steering gears, where the electronic feedback is taken directly at the rudder stock.

Twin loop systems are steering gears, where a low power actuator (telemotor) is introduced. This actuator supplies electronic feedback to the first loop. The actuator drives the input lever of the power stage, which normally has mechanical feedback to a floating lever. The power stage will normally have analog control with a variable capacity pump.

Three and four loop systems have been built, but generally with bad performance due to added deadbands and backlash, and with a high price due to high complexity. These systems should be avoided.

Five different principles of steering gear systems are commonly applied. In the following, they are discussed in an increasing order of performance regarding steering quality.

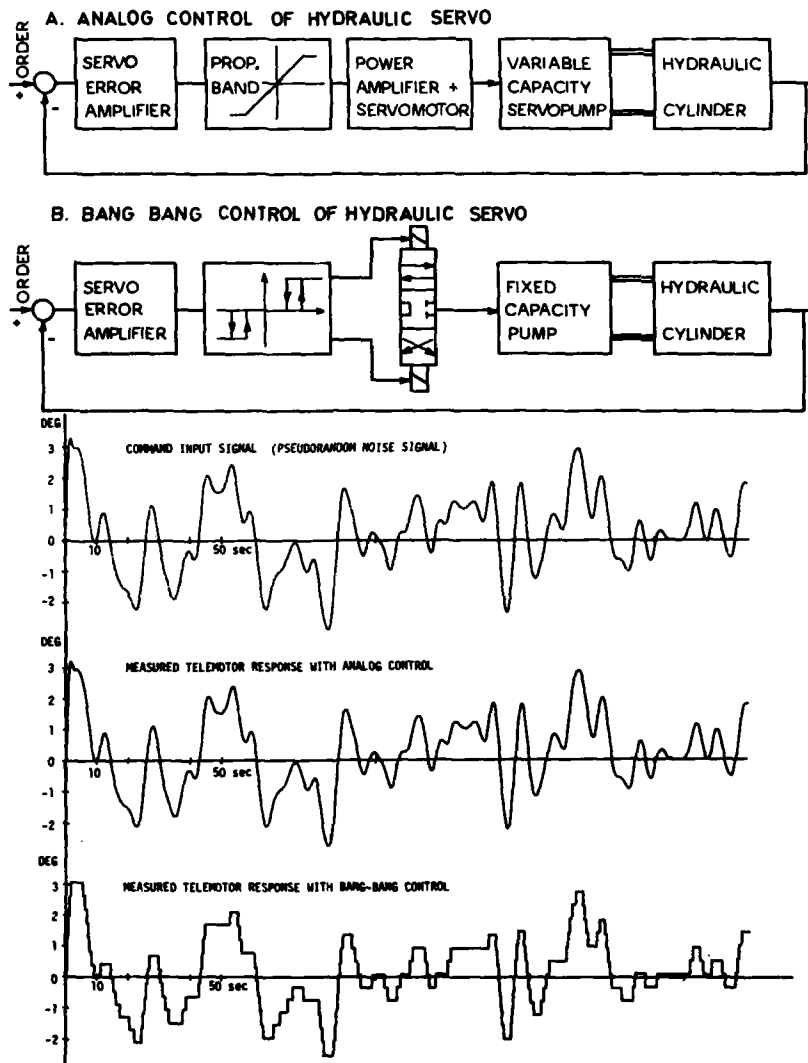


Figure 8. Analog and Bang-bang controlled steering gear loops.

Type 1. Bang-bang controlled valve in the main flow (single loop). The block diagram of this principle is equivalent to figure 8, diagram b. The output is the rudder angle in this case.

A 3-way valve directs the main flow of a pump. In the deadzone, the oil is returned to a tank at low pressure. In the PORT or STBD full speed order zones, the tank return is blocked off, and the oil is directed to the relevant port of the actuator. The other port of the actuator returns oil to the tank, often through some kind of restriction. This gives some breaking action against negative loads.

The control loop looks simple, but it will require a considerable deadband for stability. To protect equipment from pressure bursts, valve action must be slow. In high power systems two stage hydraulic valves must be used, and the result is a delay between the stroke order and the main flow. The delay is destabilizing in the servoloop. In this kind of systems the pressure transients are always considerable due to the acceleration of heavy masses, and this adds up to give increased mechanical wear.

As a result a large deadband is required in the rudder angle control loop. Deadband magnitudes between 1 and 4 degrees are normal, and the deadband will often have to be increased as mechanical parts become worn. If optimized (i.e. set up with minimum deadband) with a single pump in action, these systems will normally be unstable with both pumps running. This situation must be avoided as high power oscillations in the heavy mechanical gears eventually leads to breakdown of mechanical or hydraulic parts. In high power systems, the only advantage of these systems is a low price.

Type 2. Bang-bang controlled telemotor (twin loop). This principle is shown in figure 9 when telemotor stroke is controlled as in figure 8 b. The telemotor is typically a hydraulic actuator, driven by a small three way valve which in turn is supplied from a fixed capacity pump. Feedback is normally taken from the telemotor and led to an electronic servo amplifier with a small deadband (typically $\frac{1}{2}$ to 1 deg.). The power stage that follows the telemotor, normally has analog control, and could respond to a tenth of a degree if the telemotor servo were equally accurate.

The pump stroke, the floating lever, the telemotor travel, and the feedback link define the proportional band of the hydraulic power stage (typically 3 to 8 deg.). The power stage is a closed hydraulic circuit, and only a fraction of the available power is dissipated as heat during normal steering.

Performance of this system is considerably better than the type 1 system, and the price will be higher due to the complexity.

Type 3. Bang-bang controlled variable pump in the main flow (single loop). This principle is shown in figure 8b but with a variable capacity pump instead of the one shown. The hydraulic main flow system is a closed circuit requiring approximately symmetric actuators. The pump is a variable capacity type with stroke orders continuously variable, but due to the electric and hydraulic control circuits, it has only three states: Full stroke STBD, zero, and full stroke PORT. Compared with the type 1 full flow valve control, advantages are that stroke can be adjusted to build up gradually to full capacity in this system, and full pressure negative loads can be taken.

The circuit adds one integrator in the servoloop, so that two are in series. However, this is better than the type 1 solution with its delay, but the response of the system is amplitude dependent. Small rudder orders can be reproduced with narrow deadband settings, but then greater orders give overshoot.

Instability will be introduced at too low settings of the deadband. Values down to $\frac{1}{2}$ deg. could be used, but such low settings give

many operations of the control valve and piston so that some wear must be expected.

The same main pump could easily be equipped with analog control using a proportional valve to stroke the pump. Bang-bang control of this type of pump is therefore considered unreasonable, as analog control definitely is superior and only slightly more expensive. Bang-bang control of variable pumps could, however, be the only possibility in a period when not all autopilot manufacturers are able to supply analog output from their controllers.

Comparison has been made between analog and Bang-bang control of the same variable capacity pump, and under control from the same autopilot. With Bang-bang control, 37% higher average rudder drag force was found in seastate 5-6 than with analog control.

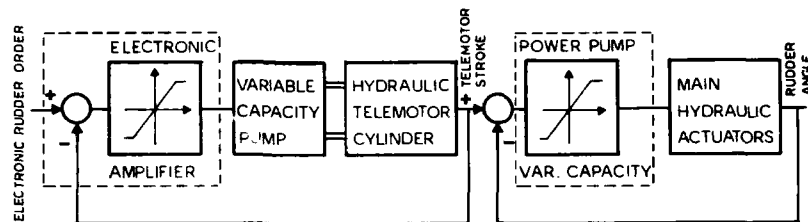


Figure 9. Twin loop hydraulic steering gear with analog control.

Type 4. Analog controlled telemotor (twin loop). This principle is shown in figure 9. The hydraulic telemotor is driven by a small pump in a closed hydraulic circuit. A servo motor drives the pump directly. A power servo amplifier controls the servo motor in a speed control loop, and stable operation to a fraction on an RPM is possible. Electronic feedback to the rudder angle servo amplifier is taken at the hydraulic telemotor. The proportional band in the servo loop could be selected within wide limits, but we have settled for 1 degree.

The power stage is identical to the one used in type 2. Although some filtering takes place in the power stage in both cases, performance of the analog system is considerably better than that of the Bang-bang system. Average decrease in steering generated drag force of a factor 2 was observed by changing from type 2 to type 4 servo principle in fine weather. The same autopilot was used in both cases.

Type 5. Analog controlled variable pump in the main flow (single loop). This principle was shown in figure 8 a where output is then the rudder angle. The system is much alike that discussed under point 3. Only the three way valve has been replaced by a proportional valve or a servo valve, and the relay amplifier in the Bang-bang system has been replaced by a linear amplifier. It is preferable to have feedback from the internal pump stroke state in the control loop, and EMRI has one system with electronic potentiometer feedback, and one where the state feedback is derived in an electronic observer. The system with potentiometer feedback will enable the highest bandwidth in the servo. The system with observer feedback will have longest life as there is no stroke feedback potentiometer that could be worn out.

The observer feedback principle is used in the SVENDBORG steering gear, supplied by ATLAS DANMARK. Figure 10 shows the servo system block diagram.

Performance of this system is excellent. Comparison with the type 1 system showed that the average rudder drag force was 74% higher than when using the type 5 analog system.

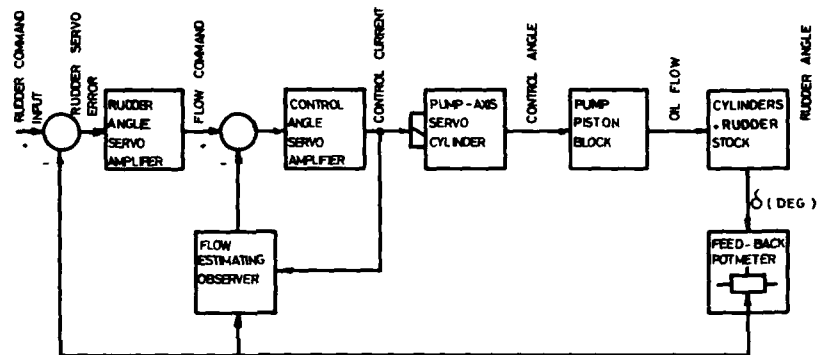


Figure 10. Analog controlled variable pump in the main flow with observer feedback (single loop).

Autopilots

The majority of autopilots on the market in 1981 are PID-controllers with adjustable rudder limit and with various types of weather damping. If the weather damping circuit is well designed, it is possible to adjust those autopilots to optimal performance at normal course keeping. It is necessary to observe the seastate carefully, however, and to change settings often if the optimal performance should be maintained. Normally navigators are not educated to do this job, and they have no long time averaging instruments to support them in the process. Also no standard instruments exist that could take the relative direction of the sea into account.

Regarding course alterations, the well trimmed standard PID-controller is able to take stable ships through manoeuvres with rate of turn controlled by the rudder limit setting. On ships which are directionally unstable, course alteration capability of the PID controller is generally not satisfactory, however. Some kind of limit in the rate of turn has to be included. A few autopilots with this feature are on the market. Relative to the number of unstable ships very few are in operation, but more are envisaged to follow.

Regarding autopilot adjustment, it has been the experience from about 100 tests and seatrials with various makes of autopilots in the past ten years, that most autopilots are not set to optimal performance. Several types can not even be optimized, mainly due to weak weather circuits. Furthermore it has been experienced that performance is rather easily improved when settings and control principles are improved. This conclusion has been drawn by other autopilot manufac-

turers also, and adaptive autopilots have resulted. A few makes of adaptive autopilots are now commercially available, and we have participated in the testing of three. In two cases improved steering was proved when compared with the "mother" non-adaptive product. The steering under higher seastates have in particular been better in both cases.

A combination of an analog steering gear and an adaptive autopilot is expected to give better results than when improving only one part of the course control loop. Comparison of the different combinations of analog/Bang-bang and adaptive/non-adaptive autopilots have been made on one ship. Test results do support these expectations.

At high seastates it becomes quite difficult to compare speed performance of two systems due to increased scatter from changing weather conditions. Sample results indicate that a speed increase of not less than 1% may be expected by using adaptive or well tuned autopilots under those conditions. Thus the poor autopilot systems give rise to a speed drop of more than 1% at high sea states due to "confused" steering.

SEA TRIALS

Extensive series of sea trials have been conducted with the purpose of measuring possible improvements in propulsion efficiency when improved control equipment is installed.

The series of test trials commenced with a set of controlled manoeuvring experiments. These were used for identification of the nonlinear speed equation. Series of short time experiments of approx. 30 minutes each were then conducted on board ships where comparison between different equipments were possible, and finally analysis has been made of speed reports from ships where control equipment was modified.

Test trials relates to four distinct groups of tests:

- a. Oscillating manoeuvre experiments. The purpose was to verify the nonlinear ship speed equation and to determine the loss term coefficients. These tests were all conducted in calm weather. (Trials with 2 ships).
- b. Measurement of propulsion efficiency during normal operation of the ship but with alternating use of one servo principle or another. The purpose was to compare the performance of analog steering with different Bang-bang systems. (Trials with 4 ships).
- c. Analysis of regular speed reports from ships where analog steering and in some cases new autopilots were installed. The purpose has been a long term evaluation of steering performance. (10 ships were analysed).
- d. Test trials were adaptive and self tuning regulators were used alternating with conventional PID autopilots. (Trials with 4 ships).

Data analysis

This section will outline the basic statistical approach taken in the analysis of test trials. Details relating to the different types of experiments are given in the discussion of each experiment. The objective of the data analysis is to separate the effects of different types of steering principles from extraneous variations due to shaft power variation or external disturbances. Based on measurements of ship speed, shaft torque, and observation of seastate and of wind-speed and of its angle of attack, the analysis is to show the average speed change. The level of confidence of this value is also informative.

Let the sequence of measurements be $y(i)$ and the other measured quantities $x(i,j)$. The estimated coefficients sought are $\alpha(j)$. We then wish to find the set of $\alpha(j)$ which gives a least squares fit to the equations

$$\begin{pmatrix} y(1) \\ \vdots \\ y(i) \\ \vdots \\ y(n) \end{pmatrix} = \begin{pmatrix} x(1,1) & \dots & \vdots \\ \vdots & \ddots & \vdots \\ \vdots & \vdots & x(i,j) \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & x(n,m) \end{pmatrix} \begin{pmatrix} \alpha(1) \\ \vdots \\ \alpha(j) \\ \vdots \\ \alpha(m) \end{pmatrix} + \begin{pmatrix} w(1) \\ \vdots \\ w(i) \\ \vdots \\ w(n) \end{pmatrix}$$

where $w(i)$ is considered to be the measurement noise on the observation of $y(i)$. In vector notation

$$y = X \alpha + W$$

The matrix W is a diagonal matrix expressing the noise covariance. The least squares estimate of the parameters α is known to be

$$\hat{\alpha} = (X'X)^{-1}X'y$$

The variance on $\hat{\alpha}$ is expressed by the X matrix and the variance σ_y^2 on Y :

$$E\{\hat{\alpha}^2\} = \sigma_y^2 (X'X)^{-1}$$

As the true variance on y is not known, it is replaced by the estimate

$$\hat{\sigma}_y^2 = \frac{1}{n-1} \sum_{i=1}^n (y(i) - E\{y\})^2$$

In this way both the parameters and their variance are obtained.

In order not to confuse data processing by including variables which are insignificant, programmes are used that disregard parameters with large variances relative to their values (Spliid(1978)). This feature is in particular useful when it is attempted to correct long term experiments for example for weather influences.

Test trials aiming loss term identification

Oscillating experiments were conducted with a VLCC tanker of 340,000 tdw and with a 14,000 tdw container ship in order to verify the nonlinear model of speed and propulsion dynamics, and in order to determine the loss term coefficients appearing in equations (4) and (8). Both static analysis and cross-bispectrum dynamical analysis techniques were employed to achieve these goals. Details have been thoroughly discussed in Blanke (1981), and some results were presented in Blanke (1978).

In these experiments, propeller characteristics were available, and several points on the resistance characteristic had been measured. Regression analysis could therefore be applied to the equation

$$R(u) = (m - X_{VR})v_r + X_{CC\delta\delta}\bar{C}^2\delta^2 + (1-t)T \quad (16)$$

where propeller thrust was estimated from the propeller equations as

$$T = T_{nn}n^2 + T_{nv}nU(1-w_0) \quad (17)$$

and

$$(1-w_0) = \frac{Q - Q_{nn}n^2}{Q_{nv}nU}$$

From several experiments where the vessel was oscillated about a straight course by means of a command signal to the autopilot, recordings like figure 11 were obtained. Note that by contrast to the commonly accepted belief, the shaft speed does not remain unaffected by hull motions. This has been found to be caused by nonsymmetric variation in wake fraction w_0 with sway velocity at the stern (Blanke(1981), Jørgensen and Prohaska(1966)).

Dynamic variations in ship speed due to controlled rudder and hull motions may be seen from equations (1) and (2) to be proportional to the square of the rudder angle and approximately the rate of turn. Due to the tight coupling between ship speed and propeller revolutions, the same may be seen in RPM. Hence analysis of dynamic variations of both ship speed and propeller revolutions can be used for assessing the loss term coefficients.

Table 1. Estimated loss term coefficients.

parameter	estimate	predicted	unit
$(m - X_{VR})c_v/c_r$	$-1.41 \cdot 10^{11} \pm 0.3 \cdot 10^{11}$	$-1.21 \cdot 10^{11}$	Ns^2/rad^2 *
	$-1.31 \cdot 10^{11}$		**
$X_{CC\delta\delta}\bar{C}^2$	$-2.1 \cdot 10^6 \pm 1.7 \cdot 10^6$	$-5.3 \cdot 10^6$	N/rad^2 *
	$-3.3 \cdot 10^6$		**

* = result from static analysis
 ** = result from dynamic analysis

Based on both static and dynamical analysis, the results were obtained which are listed in table 1. In the table, the factor c_v/c_r is the

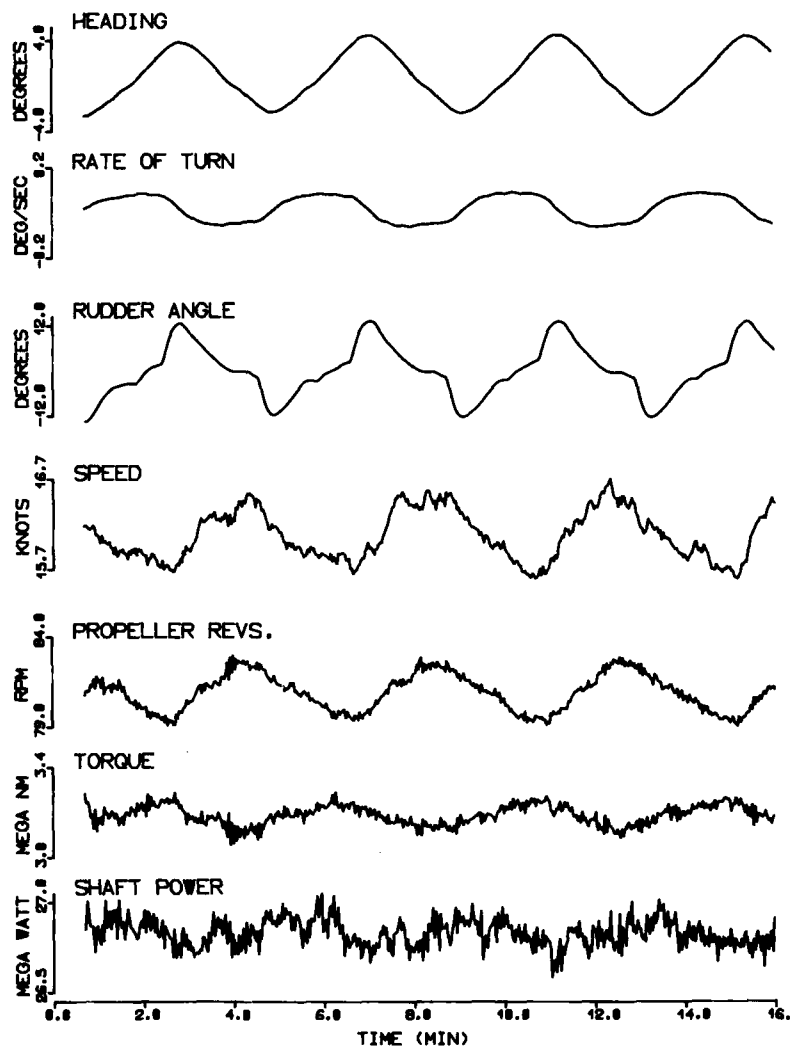


Figure 11. Record from oscillating test trial with VLCC tanker.

gain that relates sway velocity with rate of turn. Dynamically v and r are closely related when hull motions are brought about by the rudder. Using the Laplace transform operator s

$$v(s) = \frac{c_v}{c_r} \frac{1+s\tau_v}{1+s\tau_r} r(s) \quad (18)$$

Here τ_v and τ_r are time constants. This operator represents a lag-lead network and at the low frequencies of most steering activity, it may be approximated by the gain factor c_v/c_r . In the oscillating experiments τ_v and τ_r were available as results of identification of the steering dynamics, and the exact expression (18) was used.

As apparent from table 1, the hull loss coefficient is consistently determined from both static and dynamic analysis, and within the uncertainty, these values support the one predicted by equation (4). The spread of 21% is caused mainly by the scatter on the measurement of U , n and Q , and as the magnitude of hull loss is below 3% of total hull resistance, this is quite satisfactory. The uncertainty on the rudder drag force coefficient is 81%. Over the range of test trials, rudder drag was somewhat less than hull induced losses, and the increased scatter is caused by this fact. Nevertheless both static and dynamic analysis indicate that the theoretical prediction by equation (5) is larger than the actual value by a factor 2. In general equation (5) cannot be assumed to overestimate rudder drag force by this factor, however. Rather the results confirm that the rudder drag coefficient is not accessible from main particulars, but specific geometry and rudder profile must be considered. Equation (5) does indicate the order of magnitude of rudder induced losses, though, and it could be used in an approximate assessment or comparison, when model tests or full scale test trial results are not available.

Instrumentation for sway velocity measurement is not commonly installed on ships. In general, the average hull loss must therefore be expressed as

$$\begin{aligned} \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T (m - X_{vr}) v(t) r(t) dt \\ = \frac{1}{2\pi} \int_{-\infty}^{\infty} (m - X_{vr}) v(s) * r(s) ds \end{aligned} \quad (19)$$

where $v(s)$ is found from eq. (18). In the last term $*$ denotes complex convolution.

When hull motions are caused by the weather, sway velocity is less predictable, and equation (18) can not be used for expressing hull loss from measurement of rate of turn only. Consequently the hull loss can not be directly assessed in such cases.

It is worth noting, that for the VLCC tanker an RMS rudder angle of 4.1 degrees, and an RMS rate of turn value of 0.022 deg/s both cause a 1% increase in drag force on the ship, referred to nominal operation conditions.

Comparison of rudder servo principles

A series of tests were conducted with four ships where different rudder servo principles were used. The installation allowed for switching from one type to another. Two cases have been selected for this presentation because on both ships, the two different rudder servo systems had been installed at the same time. Hence improved quality of one system could not be caused by wear of the other. Test trials were conducted as a series of short experiments of either 30 min or one hour duration.

One experiment involved a 4,200 tdw bulk carrier. Two sets of experiments were made. In the one, ship speed was found through radar observations every 20 min. In the other, a patent log was used for finding the ship's speed through the water. The ship's normal instrumentation was otherwise employed. Results of the series of test trials are given below. The term res.spread denotes the spread on results after removing influence from for example wind, by the least squares regression.

Table 2. Results from tests with 4,200 tdw ship.

		radar observation	patent log
number of cases		48	48
average speed	[m/s]	6.70	7.16
spread	[m/s]	0.43	0.15
res.spread	[m/s]	0.11	0.12
improvement by analog	[m/s]	0.040±0.032	0.044±0.038
rel. improvement	[%]	0.60±0.48	0.62±0.53

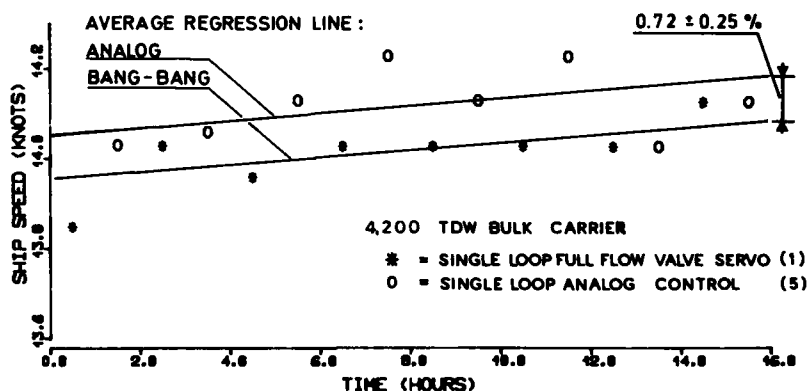


Figure 12. Results from one days experiments with bulk carrier. Data are corrected for weather.

Results from one day where patent log reading was used, are plotted in figure 12. The data shown are corrected for influence by wind, but because weather information is being somewhat arbitrarily judged and given in terms of the Beaufort scale, the scatter due to wind and sea can not be entirely removed. Both results show 0.6% speed increase at constant propeller thrust in favour of the analog system.

The other experiment involved a VLCC tanker at full load. In this case a twin loop Bang-bang and a twin loop analog steering gear servo were compared using the same autopilot. The signals measured were conditioned and averaged by the EMRI "SPICE" signal processing unit. Results are listed in table 3, and raw speed readings over 9 hours are plotted in figure 13.

Table 3. Results from tests with 330,000 tdw tanker.

number of cases		57
average speed	[m/s]	8.157
spread	[m/s]	0.17
res. spread	[m/s]	0.05
improvement by analog	[m/s]	0.019±0.017
rel. improvement	[%]	0.23 ±0.21

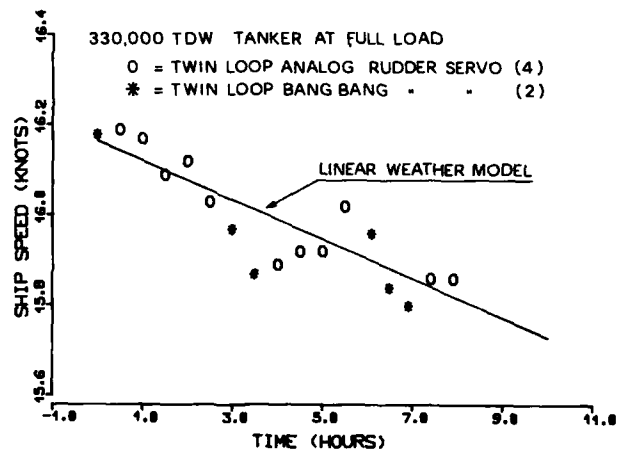


Figure 13. Results from test trials with VLCC tanker. The raw speed measurements are shown. Wind is gradually increasing during the experiment.

On the particular day which relates to figure 13, weather became gradually worse, as reflected in decreasing average speed. Each run lasted 30 min. The values plotted in figure 13 are the raw consecutive data gathered without allowing ship speed to settle after a change of rudder servo. Points following a servo changeover are therefore disregarded in the analysis. These points are included in the plot anyway, because they show how speed changes following each change of steering gear servo. The results of 57 runs as listed in table 3, show an improvement in speed of 0.2% in favour of the analog system.

In this case both steering gear servos were new, and the performance of the Bang-bang system was quite satisfactory. A significant reduction in rudder activity was nevertheless found when changing to the analog system. From a judgement of steering quality therefore, the analog system also appeared to be superior.

In the analysis it has been experienced to be rather difficult to remove weather influence entirely from the ship speed data. This is seen on the plot in figure 12, where data were corrected for estimated wave resistance and wind force, such that a least squares fit was obtained for the entire set of runs. Weather influence is present in the data anyway, however. This causes a larger spread in the results for the entire experiment than when only periods with a steady development in the weather are considered. The reason is the insufficient information on actual weather, and only direct measurement of average wind speed could improve the results.

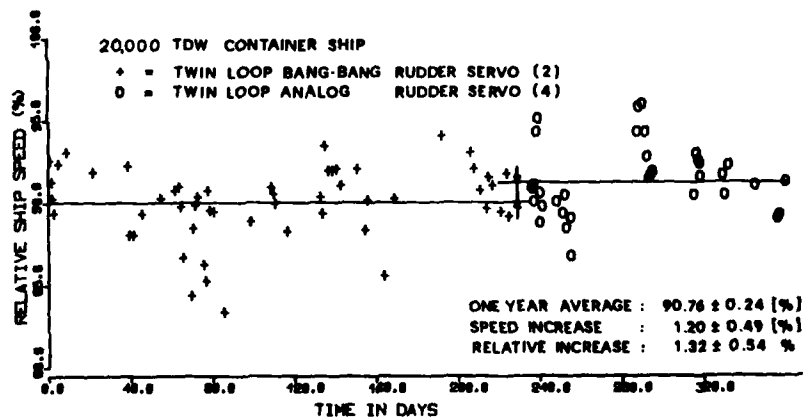


Figure 14. Relative ship speed during one year. Data are corrected for ship's draught, trim, shaft power and weather. Rudder servo was changed after 230 days.

Analysis of speed reports over extended periods

Analysis has been made of regular speed reports from ships where analog steering and in some cases, new autopilots were installed. The speed reports are measurements of the average speed over several hours at the current operating condition of the ship. In addition to ship speed, approximate averages of shaft speed, shaft power, sea state, wind speed and the angle of attack from waves and wind are provided. Furthermore parameters as ship's draught and trim are available. Based on these figures the speed data can be converted to some standard operational condition. In this process results are rather sensitive to measurement uncertainty, and as hardly any ship have long term averaging instruments for providing the readings, some scatter in the results is unavoidable. In order to obtain statistical significance, a considerable number of observations are then required. Results for two different container ships are presented in figures 14 and 15.

In figure 14, 97 observations taken over one year illustrate the performance before and after modification of steering gear servo. Despite the relatively large standard deviation of the measurements, a statistical significant improvement of $1.32\% \pm 0.54\%$ is obtained after the change.

Figure 15 shows a plot of 49 observations on another ship over a two years period. In this case the autopilot was replaced and the steering gear servo was modified. The autopilot was changed from a PI to a PID type, and the rudder servo was modified to analog control. By the combined change, an increase in ship speed of $1.92\% \pm 1.44\%$ was achieved, referring to the ship's nominal operating condition.

The speed reports have been randomly selected over the periods considered, and all observations (except some with less than 40 % of nominal shaft power) have been included in the analysis. The figures obtained therefore express the actual performance for the particular ships.

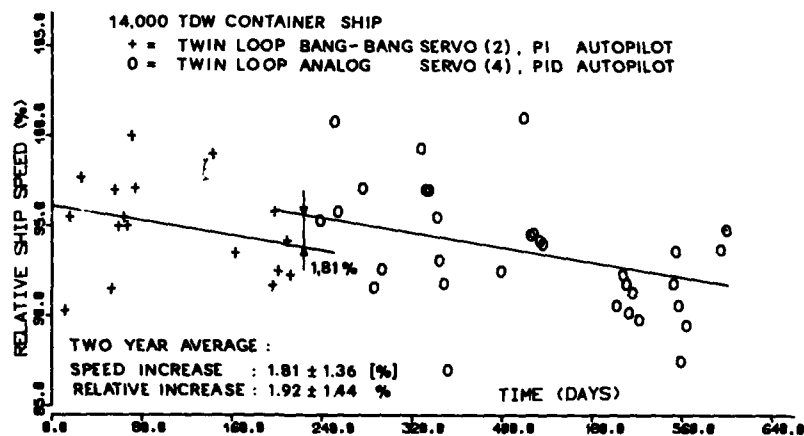


Figure 15. Relative speed referred to constant power level. Data are corrected for draught, trim, shaft power and weather.

Test trials with advanced autopilots

Several test trials have been conducted where different autopilots were compared. The diversity of autopilots available does not allow for any simple systematic treatment like that given for the steering servo, and the range of possible settings of parameters further adds to the complexity. In this context we therefore only distinguish between conventional (PID type) or advanced (self tuning) autopilots.

Test trials with conventional autopilots have shown that in calm weather, well tuned PID regulators use so little rudder and have so high course keeping ability, that neither rudder losses nor hull induced losses are worth considering. One major obstacle experienced with conventional autopilots is, however, that they are rarely set to optimal performance. Under certain conditions, considerable propulsion losses are therefore introduced.

Figure 16 shows a test trial where a PID autopilot, which was adequately tuned for deep water, suddenly introduced a limit cycle when entering shallow water. The limit cycle shown is estimated to cause 4.5% excess drag force. The self tuning regulator by contrast, was able to cope with the changed condition.

Figure 17 shows results of measurements on a VLCC tanker in ballast. On the particular day, weather increased to a maximum of Beaufort 8 on mid day. Several signals are shown on the plot. Among these, the average rudder angle and the RMS value of the pitch angle provide useful information on the weather influence on the ship. Regarding the propulsion losses, the rudder angle and the rate of turn curves are in particular interesting. The self tuning autopilot which contains a Kalman filter, uses much less rudder than the conventional autopilot. The PID regulator's higher rudder activity does not, however, reduce rate of turn compared with the adaptive. Consequently, the drag force is higher for the PID type autopilot and is reflected in lower average speed. The plot of ship speed measured by a doppler log does support this, although the spread in the speed measurements is rather large.

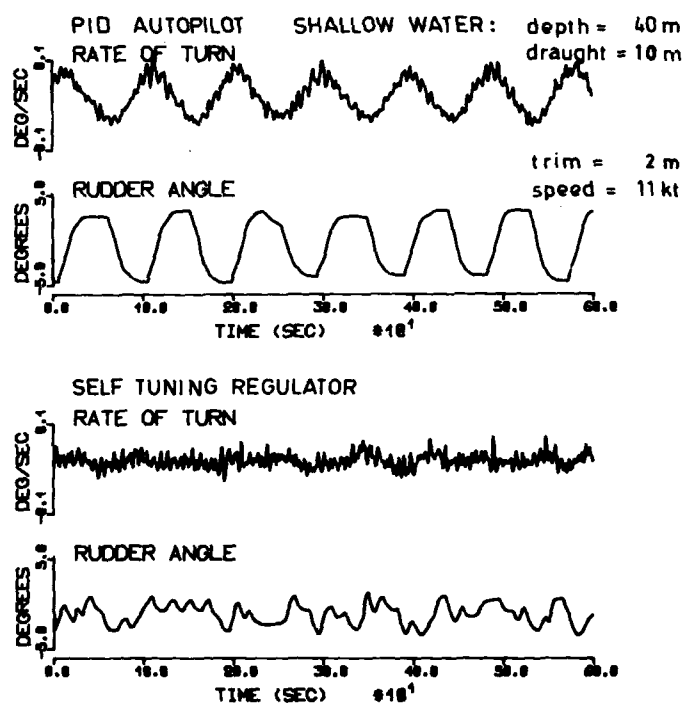


Figure 16. Recordings from test trials with VLCC tanker in ballast. Shallow water conditions. Both a PID and a self tuning regulator are installed for the test.

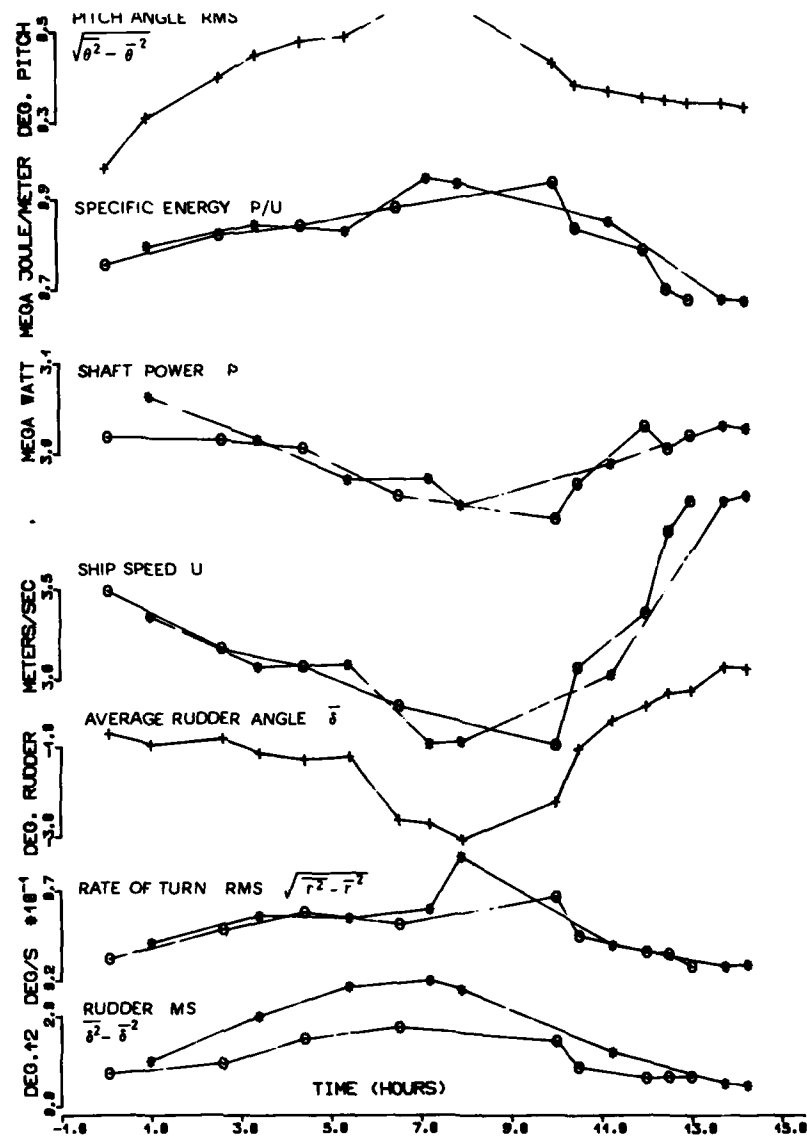


Figure 17. Adaptive (o) and PID (*) autopilots on VLCC tanker in ballast. Rough weather results over one day.
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SUMMARY OF EXPERIENCE

Rudder servo. Results from measurements are summarized and related to the different steering gear servo principles in table 4. The table lists a set of values which relate to a marginally stable ship under control of a well tuned autopilot. A low sea state is assumed.

Table 4. Expected rudder activity with different rudder servo systems

rudder servo	main pump stroking	system type	δ^2
BB single loop	fixed	1	3 deg ²
BB twin loop	variable	2	2 deg ²
BB single loop	variable	3	1.5 deg ²
AN twin loop	variable	4	1.2 deg ²
AN single loop	variable	5	1 deg ²

Autopilots. Experience from test trials can be summarized as follows:

1. Some autopilot designs can not be optimized.
2. Most standard autopilots onboard ships are not optimized, and continuing zig-zag manoeuvres have been observed.
3. In moderate weather the combinations of adaptive autopilots and analog steering gears are superior.
4. Well designed adaptive autopilots give superior steering in rough weather.

Over all steering system performance. The experience gained through the test trials discussed can be summarized and related to weather as shown below.

	WEATHER SITUATION	
	fine - moderate	rough
AUTOPILOT DESIGN AND SETTINGS	All well constructed autopilots could be optimized	Adaptive types of autopilots expected superior. Nonadapt.: Weather circuit & Setting important.
STEERING GEAR SERVO TYPE	Analog type of steering gear servo superior. 1.5 % less fuel consumption found.	Servo types becomes less important, as pumps are full stroked in greater parts of the time.

CONCLUSIONS

This paper has presented a comprehensive and unique material on the experience gained with direct measurement of steering generated propulsion losses. Experiment procedures and analysis techniques have been developed based on the nonlinear dynamics of the ship speed and the propulsion system, and also on the characteristics of the ships environment. These methods have been successfully applied for measurement of steering generated propulsion losses.

One major observation when analysing propulsion efficiency is the physically given constraint between power consumption, ship speed and excess drag force such as encountered from steering activity. If disregarding this relation, which is influenced by the prime mover control system, an analysis of propulsion losses may easily be invalidated. Propeller thrust must therefore explicitly be considered in the analysis. This fact is not believed to be generally recognized.

The major contributions of the paper are the following:

1. Experimental procedures have been developed that allow for direct and rapid assessment of steering generated propulsion losses to an adequate level of statistical significance.
2. Through the results, it has been experimentally shown how propulsion losses relate to different categories of rudder servo principles and autopilots, and figures are given which enable explicit comparison of different control principles.
3. It has been shown that contrary to common belief, the rudder servo is in general the main source of steering generated propulsion losses in lower sea states. Results also indicate that a combined system with analog steering servo and a self tuning regulator offer noticeable further improvements in conditions such as shallow water and rough weather. In addition the propulsion losses due to commonly seen misadjustment of autopilots is avoided when introducing adaptive principles.

The results presented in this paper are hoped to enhance the ability of ship owners, autopilot-, and steering gear manufacturers to choose new systems so that steering generated propulsion losses in the future will be significantly reduced.

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SHIPBOARD INTEGRATED MACHINERY CONTROL SYSTEM (SHINMACS) -
A CANADIAN FORCES CONCEPT

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ABSTRACT

The Shipboard Integrated Machinery Control System (SHINMACS) is a Canadian Forces (CF) machinery control concept that will cater for current and future control systems. The driving force behind the SHINMACS concept was the realization that digital electronics had matured to such an extent that it provided a proven vehicle whereby the CF could address the problems summarized by Reilley and Baxter (1). This paper will present the pertinent background that aided in the concept formulation and described in detail the concept, particularly the man-machine interface consoles, the computer generated graphics, the hardware/software/firmware considerations, reliability/maintainability and inherent training aspects. The ultimate aim is to design, build and test a SHINMACS Service Test Model.

INTRODUCTION

Simple mechanical control devices such as centrifugal governors and float operated valves have been used at sea since the introduction of steam. These first simple control devices were used in all naval steam turbines and reciprocating machinery built up until the end of World War II. In the post war shipbuilding program, the Canadian Navy specified pneumatic systems to control the drum water level and the superheated steam temperature for its new generation of compact, high performance Y100 boilers. The aim here was not so much to reduce manpower but to reduce the chance of human error when operating these rapid response steam generators. Manpower at the time was still plentiful and reasonably inexpensive. The Canadian Navy's next phase of shipbuilding in the early seventies saw a significant change in propulsion technology with the introduction of the gas turbine and controllable pitch propeller. Pneumatics were again selected for the propulsion plant control system with the added sophistication of electronic sequencing and monitoring equipment. The primary aim was still to reduce the risk of human error when operating highly complex equipment. A by-product of this system was the overall skill level of the engineering department onboard ship was raised due simply to the step increase in complexity and maintenance requirements. The operation and maintenance of these advanced systems was not accurately forecast and even today our training system has difficulty in producing acceptable control system technicians for all classes of ships.

The available technology which best addressed the problems of reliability, availability, maintainability, modularity, flexibility, obsolescence, training, etc, was digital electronics, specifically

the digital computer. Here was a device that was capable of promoting the integrated machinery concept. If one used digital computers, it immediately became apparent that their ability to perform thousands of instructions per second could render considerable dedicated hardware redundant and eliminate miles of cable by simply multiplexing information onto a single bus. From this initial thinking, using the digital computer as a fundamental building block, evolved the SHINMACS concept. The general intent of the concept is to utilize a serial data bus and a standard local intelligent input/output device to enable the operator and supervisor through their man-machine interface to control, respond to or interrogate propulsion control, auxiliary and ancillary systems.

REQUIREMENTS OF AN INTEGRATED CONTROL SYSTEM

There are numerous requirements of an integrated control system as it relates to the control and monitoring of a warship's propulsion, electrical and damage control systems. The following requirements, by no means exhaustive, were identified for SHINMACS:

1. provision of an interface between the operator/supervisor and the plant;
2. main propulsion machinery control;
3. ancillary and auxiliary machinery control;
4. machinery condition and health monitoring;
5. acceptable reliability/maintainability criteria;
6. obsolescence;
7. capable of being used as a training system;
8. extensive self-test and diagnostic capabilities.

The requirements listed above are not arranged in any preferential order, however, the last four warrant considerable attention since any integrated control system contemplated for current or future ships will be judged on how well it responds to these requirements. Not to address requirements 5 through 7 with any sincerity will doom the eventual system to failure for it is a fact of life that the people onboard ships must be part of the control system and not relegated to the status of bystander.

To complement the set of requirements for SHINMACS, the Canadian Forces envisaged the need for a set of design objectives that would place some recognizable bounds on the conceptual iteration process. A set of realistic design objectives were considered necessary if the concept was to be eventually realized in the form of a Service Test Model. For the purposes of the discussion in this paper, a Service Test Model is defined as a model of the system which can be used for test under service conditions to evaluate its suitability and performance. The model should closely approximate the final design, have the required physical form, employ approved military parts and be fully capable of performing in an operational ship.

The set of design objectives used and a brief explanation of their intent is as follows:

1. Survivability: Battle damage to any cable or equipment of the system or any single failure should not catastrophically affect or interrupt the control and monitoring provided by SHINMACS.
2. Reliability. The system should be designed with sufficient protection to ensure continuous operation under adverse operational or environmental conditions. The integrity of SHINMACS should be maintained to prevent the system from any inadvertant data modification, service interruption or system malfunction due to a hardare, software or firmware failure.
3. Redundancy: Sufficient redundancy design of the system should be implemented to ensure that the vital control and monitoring functions provided by SHINMACS are uninterrupted when the system is exposed to adverse operational or environmental conditions.
4. Modularity: The system should be designed with maximum software, firmware and hardware modularity to provide system expandability, maintainability and flexibility.
5. Flexibility: With stored program control and modularity of design, the system should be capable of being easily changed, expanded, reconfigured and updated to meet future changes in operational requirements without hardware modifications.
6. Standardization: Standardization of hardware, software and physical connections should be strived for to permit maximum interchangeability.
7. Graceful Degradation: Catastrophic failure of the system should not be permitted. If the system is degraded by multi-failures, continuous operation of the vital control and monitoring systems should be maintained.
8. Obsolescence: To prevent the system from becoming obsolete, anticipated changes and developments in future marine control system technology should be considered. The software design should render the system immune to operational obsolescence.

With a set of SHINMACS requirements and design objectives it was then possible to seriously consider placing the concept on paper. In the ensuing iterations two architectures developed; these will be described later.

RELATIONSHIP TO SHIPBOARD INTEGRATION PROCESSING AND DISPLAY SYSTEM (SHINPADS)

A key consideration in the SHINMACS concept was determining the role SHINPADS should play, if any. In the interests of standardization (one of our objectives) and to minimize the anticipated effort in software development it was decided to utilize SHINPADS hardware,
M2-3

software and firmware. For those unfamiliar with SHINPADS, reference should be made to Carruthers (2)(3) and Ironside (4) for a thorough discussion of the topic. To aid in the understanding of the architectures to be presented later, a brief explanation of the SHINPADS Serial Data Bus System (SDB) is in order. The SDB is a high performance bus-interconnect system capable of supporting up to 256 users. Bus Access Modules (BAMS) provide the basic connection to the bus cables that comprise the control and data channels. Nodes, which are connected to the BAMS provide the necessary control, management and interface capability of the bus users. A user of the SHINPADS SDB must contain a computer (for example an INTEL 8080 or AN/UYK 502) in his hardware to be able to handle the interface protocol. To enhance the SDB reliability six separate cables are used with any two of the cables capable of being designated the control or data cable. Stab cables provide the connection between a node and any one of the six cables.

SYSTEM ARCHITECTURES

In developing the SHINMACS concept the pros and cons of the various combinations of centralized, federated and distributed systems were considered. It was decided that distributed systems satisfied the majority of the design objectives, particularly the survivability, reliability and redundancy aspects. The main attraction of distributed systems for the Canadian Forces was the ability to physically locate a digital processor (generally a micro-computer) anywhere in the ship and have it execute assigned tasks independent of the rest of the system.

The architectures depicted in Figures 1 and 2 are considered to be candidates for a SHINMACS Service Test Model. The attributes, advantages and disadvantages of these architectures will not be presented in this paper rather a brief discourse on the hardware/software involved and how the architectures conceptually differ will be outlined.

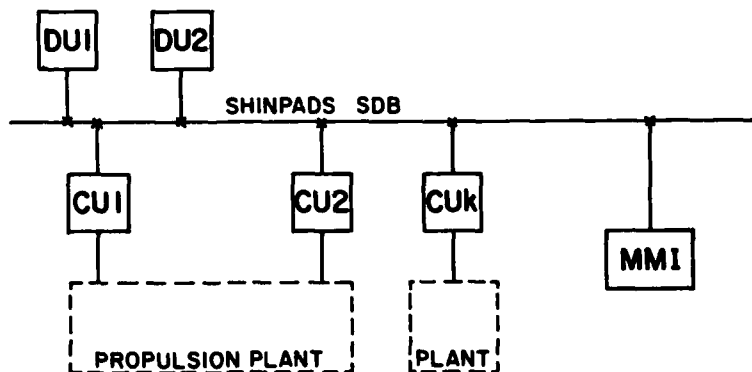


FIGURE 1
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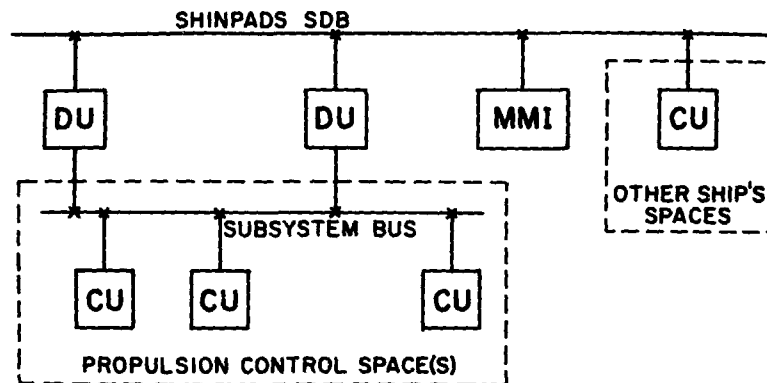


FIGURE 2

In the early development of both architectures the Canadian Forces were driven to a large extent by standardization which is evident in Figures 1 and 2. The Data Units (DUs) and Control Units (CUs) will be AN/UYK-502 computers. However, in Figure 2 there is an option to use a non-standard computer for CUs. Of course this non-standard device must meet military requirements and not jeopardize system reliability. A standard computer language (CMS-2) was also selected since it is supported by the AN/UYK-505 and 502 and the Canadian Forces has a dedicated software support facility. To choose any other language, excluding possibly ADA if it were available, would not have been practical. The SHINPADS SDB will supply the main communication mediums as well as the executive software (SDEX-20) to enable a DU to be the SHINPADS system monitor (see Carruthers (2) and (3)). The man machine interfaces (MMIs) will be integrated control consoles utilizing the Standard Display currently being developed is part of the SHINPADS program.

Standard digital equipment, as defined by the Director General Maritime Engineering and Maintenance, is mandatory if the proposed software/firmware involves re-design at a later date to comply with a change in system requirements. The CUs in Figure 2 would be dedicated to a specific task and would execute instructions derived from control algorithms resident in the DUs thus they need not adhere

to the standard digital equipment requirements. The algorithms resident in the DUs may be changed at some time, thus the DUs must use standard digital equipment.

The architecture of Figure 2 is potentially less costly to implement in that the SHINPADS reconfiguration capability is degraded somewhat and the CU need not utilize standard digital equipment.

SYSTEM OPERATION

The operation of the architectures shown in Figures 1 and 2 will be briefly described here.

With reference to Figure 1, each CU and DU would interface to the SHINPADS SDB and would be responsible for executing allotted tasks. The DUs would carry out the following:

1. system monitor;
2. bus interface;
3. plant condition and plant health monitoring applications; and
4. interactive propulsion plant simulation controller.

While the CUs would be required to carry out:

1. bus interface;
2. applications algorithm processing; and
3. plant input/output.

The supervisor and operator man-machine interfaces would be an interactive console utilizing CRTs. These interfaces would enable personnel to examine plant status, alter control parameters or engage in interactive plant simulation. In an operational system the DU currently assigned as the system monitor would continually check itself and be checked by the other DU for correct operation. Any degradation of the system monitor function would automatically result in the other DU assuming the system monitor function. The changeover, if required, would be transparent to any CU connected to the bus. An additional task of the DU would be to select one of the three buses as the active bus. The CU would essentially be an applications machine responsible for executing assigned plant tasks. It is entirely possible that to achieve the level of reliability required, redundant CUs may be necessary.

In the case of Figure 2 the DU would function in a similar fashion as described above except the DU would now be responsible for the additional tasks of being a system controller (ie, it would poll the CUs and grant bus access on some priority basis) and for executing system algorithms. The CUs instead of interfacing to the SHINPADS bus, would now interface to a subsystem bus. The subsystem bus would be associated solely with the propulsion machinery compartment(s) and would not run the length of the ship. Of course, in the event that SHINPADS was not fitted in a ship, the subsystem bus would extend throughout the ship.

THE MAN-MACHINE INTERFACE

As the ship's engineers no longer stand their watches in the machinery spaces in close proximity to the machinery itself, the man-machine interface (MMI) is their main link to the plant. It must be designed to allow an operator to supervise the operation of the machinery with a minimum of training directed toward operation of the console. Many industrial installations and some recent marine systems have been able to improve the lot of the operator or watchkeeper by the use of integrated control consoles designed around one or more cathode ray tube (CRT) displays. The advantage for a continuous watchkeeper is that he is no longer required to scan a plethora of gauges and dials in order to maintain a mental picture of the behaviour of the machinery. The CRT acts as a window into a large array of data which may include parameter readings in digital or graphic form, messages and schematic system diagrams which can be overlaid with data updated in real time. It is now possible to relieve the operator of the taxing requirement to memorize a host of systems and their relevant data by using the computer to assist the operator. An immediate advantage is to reduce the likelihood of catastrophic errors.

The MMIs envisaged in the SHINMACS concept, as shown in Figure 3 and 4, are a dramatic departure from Canadian Navy practices. The MMIs will utilize electronic CRT displays, sophisticated computer generated graphics and have access to every conceivable form of system information. The operator/supervisor through his MMI will be able to control, respond to or interrogate propulsion control, auxiliary and ancillary systems. The capability of being able to look at a system in overview form, as in Figure 5, or selectable subsets of the system complete with relevant operating parameters and status information will greatly enhance the operators effectiveness. Consider the impact of being able, at the press of a button, to request data, such as that in Figure 6, and have the data presented in graphical format almost instantaneously. The possibilities of being able to present the operator/supervisor system diagnostics and "preferred options" are very appealing. To take advantage of the capabilities inherent in the SHINMACS concept the Defence and Civil Institute of Environmental Medicine (DCIEM) were tasked to study the human engineering aspects and present an MMI design incorporating the features mentioned above. The results of the study are presented in detail by Gorrell⁽⁵⁾. The MMI design is briefly reviewed here.

The operator's console utilizes three general purpose CRTs for its main information displays (Figure 3). The three screens provide, in a structured format, the information the operator needs at any given time. The operator can select whatever information he desires by simply pressing the appropriate key or invoking a build display option. Automatic and manual control of gas turbine engines and propeller pitch is performed using four port and four starboard joysticks. In automatic propulsion mode, shaft RPM and propeller pitch are determined by demand schedules automatically from linked or unlinked port and starboard joysticks. The supervisor console utilizes one general purpose (CRT) (Figure 4). This screen could display all the pages held in the operator's console.

MAINTENANCE

Decreased maintenance costs will be one result of standardization in the SHINMACS concept, particularly noticeable if SHINPADS were to be fitted in the same ship. Spares carried onboard will be reduced compared to what would be required if every system used different computers and displays. An offshoot of standardization, but an important cost item, is the reduction in the number of drawings and manuals required. The incorporation of built-in test routines in the CUs, DUs and MMIs and a maintenance panel capable of exercising the system will greatly enhance the maintainers' lot. The diagnostic features will provide to the maintainer visual indications of the health and condition of the CUs, DUs and MMIs. The diagnostics will be designed to isolate any failure to at least board level. It is anticipated that each diagnostic could be enhanced by the availability of stored information to elaborate on the diagnostic. For example, the stored information could define the type of fault, probable cause, implication (ie, possibilities of operating in a degraded mode) and method of repair. It is also possible, that given proven health monitoring and trending routines, condition-based maintenance would become a reality.

TRAINING

An inherent feature of the SHINMACS concept is the ability to place a simulation of the propulsion plant (or any plant) in non-volatile memory and then use it to train operators. It is practical to assume that the simulation could be run concurrently with the propulsion plant running by simply relinquishing control to the bridge. The worst case is that the operator could only be trained by using the simulation when the ship was alongside and the propulsion was not required. The latter case is infinitely better than the current situation. A typical training scenario would have the instructor at the supervisor's MMI console request that the simulation be loaded. Once the simulation was ready to run the operator under training would be alerted on one of the displays at the operator's MMI that the simulation had begun. The instructor could now enter faults to cause the plant being simulated to depart from normal, the trainee would respond and subsequently be evaluated by the instructor. This ability to train an operator at any time is very attractive, not to mention cost-effective.

CONCLUSIONS

The SHINMACS concept is a radical departure from previous warship machinery control systems. The departure is prompted by necessity because the Canadian Forces must solve the problems and dilemma discussed by Reilley and Baxter (1). The man-machine interface consoles and the training capabilities of SHINMACS will help immensely.

The modularity, flexibility and standardization that will be part of SHINMACS will cater for changing operational and manning requirements. The minimum manned ship concept could be implemented at substantially reduced cost. The ability to generate complex system diagnostics will reduce downtime and ease the load of the maintainer.

The available technology, in particular the silicon chip, will make concepts such as SHINMACS real; it is only a matter of time

before it is fitted in ships of the Canadian Navy.

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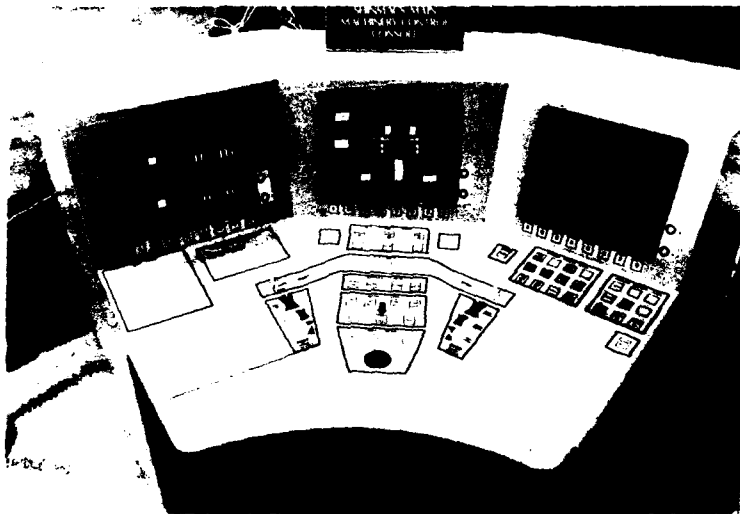


Fig. 3 SHINMACS Main Machinery Control Console

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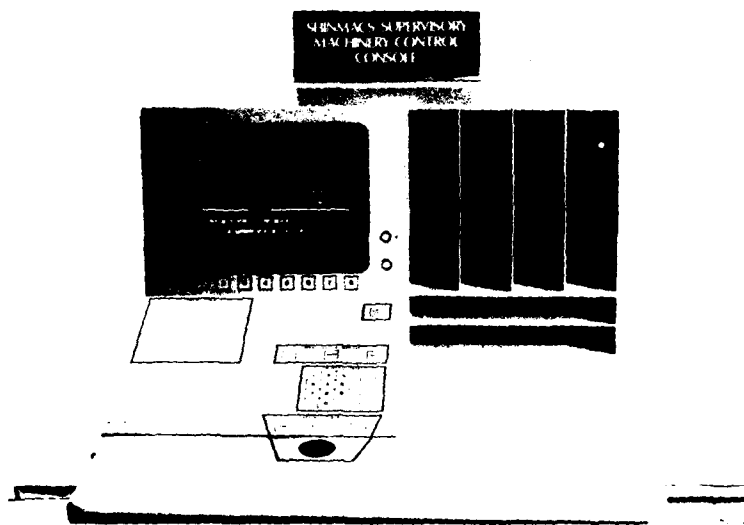


Fig. 4 SHINMACS Supervisory Machinery Control Console

PORT START STOP

STARBOARD START STOP

GENSET

THW. & PLUM. BRG.

TURB. METER

PLUM. BRG.

THW. BRG.

STERN THIBE BRG.

H. BRG. BRG.

T. BRG. TEMP.

P. BRG. TEMP.

F. WATER FLOW

F. WATER PRES.

STATUS

HOLD

Fig. 5 Shaft Data CRT Page

M2-13

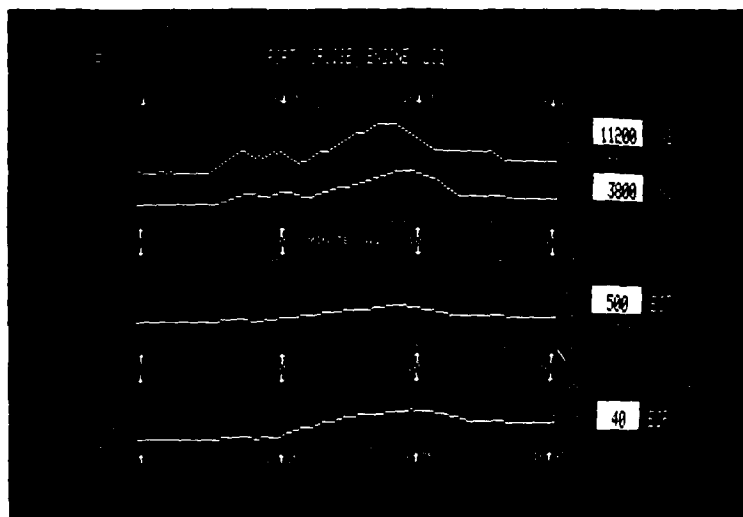


Fig. 6 Engine Log CRT Page

THE DESIGN OF MICROPROCESSOR PROPULSION CONTROL SYSTEMS

by W.S. Dines
Hawker Siddeley Dynamics Engineering Ltd (UK)
and A.F. Wesselink
Lips B.V. (Netherlands)

ABSTRACT

The Systematic approach adopted for Microcomputer Control is described and some comparisons with comparable Analogue systems are made.

The revised methods of working with Modular Hardware and Software for the design of digital systems are examined, including a "new" modular technique for the definition of control functions. This technique follows the well-proven software disciplines of top-down, bottom-up design. The flexibility of this approach is demonstrated in the discussions of system commissioning, through the path of Integration on a simulator, to system optimisation during trials by changing constants in the dedicated system memory.

1. INTRODUCTION

1.1 The need for Control

Since the time of seagoing ships man has strived to increase the efficiency. At one side he tried to increase the comfort and on the other side to decrease the energy consumed.

The ships operator wants to control the vessel in the horizontal plane in the most efficient way. He either controls the vessel position or its derivative the velocity (x , y and ψ or dx/dt , dy/dt and $d\psi/dt$, see fig.1).

To achieve control of the vessel propellers, rudders, transverse thrusters, etc. are used. These devices are configured in the optimum way with respect to the ship's operating profile.

The control systems can be divided in two areas:

- Positioning control.
- Speed - control.

For positioning control the x , y and ψ - values are controlled in a closed loop. which takes care of the most efficient force distribution among the devices.

For speed control the dx/dt - and $d\psi/dt$ - values are controlled in an open or closed loop.

The closed loop systems ask for high accuracy controllers. From the original open loop systems we have now come to the stage of adaptive controllers. This requires high capability control systems.

Besides the control systems there is the need for supervisory systems to increase the safety of operation.

1.2 Types of Control System

Mechanical control systems have developed from the simple open loop levers and rods, to closed loop mechanical, hydraulic, pneumatic systems or a combination of each. While these controls are reliable and well understood, they suffer from a lack of versatility and are relatively slow in their action. The power of the hydraulic system is still necessary to actuate large items of machinery such as propellers, but the use of pneumatic control is most unlikely in future systems. Electronic controls have now shown that their reliability in the marine environment is good, and their enhanced capability is necessary for the precise and demanding requirements of modern ships.

Two types of electronic controls are available, analogue and digital. The former has been in use for some years, beginning with discrete components and advancing to integrated circuits with their higher system reliability and compactness. Analogue system hardware has to be designed for each specific requirement, and any new requirement involves changes to components and routine circuits. This is a time consuming task and creates unique spares. However, for simple control requirements, analogue systems still have a possible economic advantage over digital systems.

However, digital systems are immediately more attractive when control systems are required to carry out more and more complex tasks. When only large computers were available, price as well as unavailability of suitable computers prevented the use of digital systems for general shipboard use. The advent of microprocessors and associated components have enabled low cost microcomputers to be built. These no longer require special environments and are fully compatible with shipboard use.

The advantages of microcomputer controls over other types are that they are extremely reliable particularly as relatively fewer components are required and hence its size is smaller. Their capability is greater than comparable analogue systems due to their ability to carry out more complex calculations with greater accuracy. A major advantage is their flexibility while using standard hardware, being able to be reconfigured for changes in system requirement without the need to alter the hardware. This flexibility is achieved by the programmed software which is stored in the memory of the computer.

While good hardware is necessary for digital system reliability, equally good software is essential for system integrity and long life flexibility. Structural, or modular, software has the advantage that it can be rigorously developed and tested before being integrated with the hardware. New modules can be added without detriment to the remainder.

The positional information can be received from radar, gyrocompass and other measuring equipment. The health of the propulsion devices can be continuously monitored.

2.4 Special Applications. The control system is not restricted in its application because of hardware limitations. Due to a modular software approach a variety of systems can be built. Fig. 7 shows a double ended ferry equipped at both ends with a feathering controllable pitch propeller. The vessel can be operated from two bridges. A single micro-computer controls both engines, the clutches, shaft brakes, propellers, and the rudders during sideways movement.

3. HARDWARE

3.1 The design of a digital system comprises two interrelated parts, the hardware and the software. Once these are defined in overall system terms, their design can be progressed separately until the time when they need to be integrated to make a complete system.

3.2 In order to meet the needs of different propulsion machinery types and configurations, a suite of standard electronic modules have been designed to cover most requirements. The design is such that specialist modules can be added as required, these in turn adding to the total suite.

3.3 The electronics are designed using the standard sized double euro-card printed circuit boards, mounted in 19 inch (483 mm) racks (fig. 8), and are designed to meet the rugged requirements of merchant ship classification societies and most naval specifications. All the systems are designed to meet naval shock specifications and the vibration levels of Lloyds. The electronic enclosures are spray proof. The temperature range is normally 0°C to 70°C, but by the selection of usually more expensive components the range is increased from -25°C to 85°C.

3.4 The choice of the Intel 8085 processor is based on the 9 years industrial and aircraft control experience gained by HSDE. It is a well supported processor whose development equipment is compatible with earlier and later Intel processors - a major factor with high cost computer development equipment. While the packaging of marine electronic controls is of necessity different to industrial units, the circuit designs are taken from the long experience of the industrial controls.

3.5 The basic suite of modules comprises a Power Supply Unit (PSU), the Central Processing Unit (CPU), Analogue and Digital Input/Output Interface modules. Specialist interface modules such as Current Drive modules have also been manufactured. The Interface modules have been designed for the optimum number of inputs and outputs found in a control system, additional interface modules being fitted where necessary. However, the CPU module also contains a limited set of interfaces for use in simple systems. With this flexible system, a common CPU module can be used with a large range and type of interface, with only a change in software.

3.6 The CPU (fig. 9) contains the processor chip and the memory, as well as the aforementioned interfaces. From the figure it can be seen that not all the memory capability has to be used on every occasion. Addressable memory is in both PROM (Programmable Read Only Memory) and RAM (Random Access Memory), the PROM is split into main programme

memory and parameter memory. The latter is the part where the specific ship variable parameters, are held. This means that 'standard' CPUs can be built and tested and the CPU can be made suitable for particular vessels by programming the parameter memory. Thus, when the control system requirements are changed, only the CPU module has to be replaced with one of identical hardware design, but fitted with a revised parameter memory and extra PROMs can be added to extend the programme.

3.7 The CPU module also contains specialist chips which permit arithmetic calculations to be made without the need of additional software modules which would slow down the processing.

The architecture of the Intel based system is shown in Fig. 10, the main features of which are described below:

3.8.1 Multiplexed Bus. The Intel 8085 is a complete 8 bit parallel CPU device using a multiplexed Data Bus. The Address Bus carries the bits of the address, which are used to identify a memory or input/output (I/O) location for a data transfer cycle. The eight lines of the Data Bus are used for the parallel transfer of data between two devices.

3.8.2 Machine Cycles. The 8085 interfaces with both memory and I/O devices by means of Read and Write machine cycles, the timing of which are practically identical. During each machine cycle the 8085 issues an address, a control signal, and then either sends data out on the bus or reads data from the bus.

The 8085 may read data from a number of sources such as Read Only Memory (ROM), random Access Memory (RAM), an I/O device, or a bank of switches. However the Read cycle differs for information read from memory, an input port, or an instruction opcode, only in the manner in which the CPU interprets what it has read.

The CPU executes one machine cycle at a time, one instruction at a time, in sequence unless told to do otherwise. The programme totally controls the sequence and nature of all machine cycles.

3.8.3 Memory Mapped Input/Output. Within the system use is made of a technique referred to as Memory Mapped I/O. Under this system, the I/O devices are connected to the memory control lines and respond like memory devices.

This technique takes advantage of the larger instruction set that references the memory address space. Thus, instead of simply being able to transfer a byte of data between the accumulator and the I/O port, the programme can now perform arithmetic and logical operations on the port data, as well as move the data between any of the internal registers and the I/O port.

3.9 The Dynalec 2000 system has been designed for high reliability, and ease of maintenance, thus providing high availability. Theoretical Mean Time Between Failures (MTBF) have been calculated, based on UK national statistical data amended by actual MTBF failure statistics obtained from the considerable HSDE records. Theoretical system MTBF's are calculated to be at least 16,000 hours compared to 6,000 hours for a comparable analogue control system. Past experience indicates that the actual MTBF will be higher, once sufficient statistical evidence is available. Increase in programme

complexity only affects memory, and system reliability does not decrease as no additional components are fitted.

3.10 The majority of fault finding is done with an off the shelf interface unit (fig. 11). This enables the maintainer to interrogate the digital system, identifying faulty module parameters.

3.11 During system development, the software is integrated with the aid of a Microprocessor Development System. However, this is a large unit. Thus programme adjustments during commissioning and trials require a more portable unit (fig. 12). The parameter PROM is removed and replaced by this unit which contains the memory in RAM. Using a keyboard it is possible to adjust the memory. When correct, the same unit is used to programme the PROM which is finally replaced in the CPU.

4. SOFTWARE

4.1 The designer of software for micro-computers has two choices, he either writes the programme in machine code or in a high level language. The former choice is applicable if the task is simple, dedicated and never to be changed, or whose memory size is at a premium. The disadvantage is that it is particular to the author and required considerable learning if someone else has to revise the programme. It is also difficult to test the software.

4.2 For the Dynalec 2000 system the Intel 8085 mnemonics are used, but the programme is written using a modular methodology. With a modular organisation, each system function can be written on its own and grouped with other modules to carry out more complex functions. There are a number of advantages to this design approach:

- (a) Each module can be written and fully tested on its own.
- (b) Modifications to any one module do not require testing of the whole software, but only the module which has been modified.
- (c) Standard modules can be configured into new systems with the minimum of new software being written.
- (d) System testing of software begins with individual modules, which are grouped and tested in ascending complexity. This is known as the 'bottom-up' approach to software testing.
- (e) Having standard modules provides the incentive to maintain good documentation, which is the key to well supported digital systems.

4.3 The modular approach to software design is illustrated in figure 13 which is a typical example of the module required for vessel position control system. Each standard module represented in the small circles is "tied" to the overall software by the software system control programme. The system control has to be tailored for each application, but in most cases it will be simple variations of a previous application.

4.4 One of the problems of digital system design is to make the system designers requirements easily understood by the software designer, who may have little systems knowledge. It becomes even more

important when systems are similar, but have individual requirements, and where design costs must be kept to a minimum.

4.5 Therefore, HSDE and Lips are developing a standard function description format which is tailored to the requirements of their particular propulsion control requirements. This format is modular in construction like the software itself. At present this format is being developed and its library of modules increased as experience and different functions arise. It is based on ideas used in large simulation techniques such as CSMP (reference 5)

4.6 Just as it eases design definition this format, which has been called SIMPLE (System Into MicroProcessor Language Equivalents), assists in the integration and testing of the software and hardware as all the design and development disciplines involved understand what is required.

4.7 The modular software is written and linked on a mainframe computer, only being downloaded to the deliverable system for integration after extensive testing. This technique has the advantage that the hardware, integration tools (Microprocessor Development System MDS and In Circuit Emulator, ICE) and the additional engineering effort required for integration are only required for a short period prior to delivery. This avoids the need for long integration periods due to loading and integrating partially tested or untested software too early in the software design, which leaves all the problems to be solved on the MDS and ICE during the critical period prior to delivery.

4.8 The software modules are "plugged" into a standard software input/output and real time "frame". An example of the resulting operating levels and sequence of procedures is shown in fig. 14.

4.9 The Dynalec 2000 system is 'Interrupt Driven'. At start up the system goes through an initialisation routine and then into the main programme cycle which is a continuous loop. The Timer Interrupt is used to schedule the time dependant routines listed. These time dependant modules are scheduled to run as frequently as necessary. For example Rate limits are 16 times per second, Timers are 2 times per second. The interrupt also initiates the Analogue to Digital Conversion (ADC) by addressing the required Port, before returning to the main programme loop. Similarly if a diagnostics routine is received via the V24 link, the system jumps to the V24 handling routine.

4.10 The system thus spends most of its time on the Main Programme cycle at Level 0, jumping to higher levels 1,2 and 3 either by timer or specific interrupts. The advantage of 'Interrupt Driven' over sequential processing is that important routines or events are run as required, rather than waiting in a queue of sequential actions which are completed in turn regardless of their importance.

5. TESTING

Besides testing the system on the software level the total system, software and hardware, has to be tested. During this system-integration the hardware together with transducers and panels is tested.

A simulator which models the equipment and ship to be controlled, provides the input and output signals.

5.1 The Simulator. Control systems have to be tuned to the process being controlled. In other words the behaviour of the process should be known or adjustments must be done by "trial and error". Trials are expensive, but errors are even more expensive. Hence the use of a simulator for tuning is very desirable for any but the simplest systems.

Parts of the propulsion system can be described by polynomials, characteristics or transfer functions which can be interconnected. The connections represent physical values. Such a function block diagram can be made for all kinds of processes. The prime-mover can be a gas turbine, steam-turbine, electric motor or diesel-engine. To achieve the simulation data a mathematical model is made by means of analysis and measurements of a device. The constants for this model can be calculated or measured. For standard products, programmes can be written to calculate the constants from data gathered from drawings.

Fig. 15 shows such a block-diagram for a single propeller/single diesel engine vessel. The propeller is of the controllable pitch type.

The block-diagram contains two main control loops: the revs. - and the pitch control-loop.

The pitch is controlled in two loops. The main loop (CPP-system) contains a mechanical/hydraulic controller for the hydraulic cylinder adjustment. In fig. 16 these two control loops are shown (see also refs. 3 and 4).

The shaft speed control loop contains the diesel-engine. The shaft speed is controlled by the rpm controller. The diesel-engine with the attached inertia systems can be described as a series connection of first order systems and a dead time. A non-linear element for coulomb-friction is necessary. A more detailed approach is sometimes desired, e.g. for studying the temperature behaviour of the engine (ref 7).

In order to avoid unfavourable operation conditions for the engine a load-controller is included in the control system. A logic module selects between load-control and remote-control. The pitch and shaft speed are inputs to the propeller system. Ship velocity is also an input.

The propeller is described by polynomials by means of which the torque and the thrust are calculated. The torque is fed-back to the diesel-engine.

The thrust is an input to the vessel system described by its mass and resistance.

The model can be extended for twin engine drive, a twin screw vessel, power take-off systems etc.

A further extension is simulation of a vessel with multiple propulsion devices (ref. 4).

Considerable experience with this simulation approach to system testing has been gained, reducing ship testing time.

5.2 Simulation and system integration. The simulator is first adjusted and all time-constants, gains, and schedules are set.

The next step is the connection of the actual hardware to the simulator. The hardware consists of the electronics unit and the control panels.

The parameters are adjusted by means of the micro-computer development system (MDS) and in circuit emulator (ICE) under simulation.

Once the programme is correct the main programme - and the parameter PROM are "blown".

After the simulation the system is kept powered for at least 50 hours to avoid "infant mortality failures". During this period the system can be used for training purposes for the commissioning engineers and the future crew of the vessel.

6. INSTALLATION AND TRIALS

Due to the extensive simulations the time for installation and trials is shortened.

6.1 After delivery to the shipyard, the units and panels are installed and their interconnecting wiring is connected. Wiring to the propulsion machinery is prepared but not connected.

6.2 Once electrical power is available, the engineers start checking the installation and wiring. They connect the wires to the controls units and panels after checking the propeller and the primemover with the representative of the manufacturer.

Normally, for an average system this checking and wiring connection takes one or two days.

6.3 When the system is checked finally it is energised. All the transducers and actuators on the prime-mover and controllable pitch propeller are checked, and if necessary re-adjusted. The next step is the check of the panels. Outside systems, such as gyrocompass signals, etc, are connected and checked. This stage of the installation is of very great importance. The time spent depends strongly on the size of the vessel, the complexity of the system and the workmanship of the yard. Sometimes it takes only one day, sometimes 25 days.

The micro-computer controlled process can be checked quickly due to the powerful tools: diagnostic unit and parameter adjustment unit, described in section 3.

6.4 The system can then be checked together with the yard. After acceptance the system is ready for trials.

6.5 During trials only fine-adjustments are necessary. The proper working is checked by specified vessel manoeuvres. Most of the adjustments are done in parallel with other sub-contractors. For an average speed-control system only one to three hours are directly

necessary. A positioning control system requires some more time due to the special manoeuvres (see ref. 4). This time varies from 2 to 24 hours.

7. CONCLUSIONS

7.1 As the requirement grows for more complex propulsion control systems the advantages of micro-computer based electronic systems can be readily seen. Standard hardware can be used where only the memory chips are changed to accommodate all the ship type variations. The capability of processors with specialist chips to carry out arithmetic functions means that complex algorithm calculations can be carried out accurately and easily without large increases in hardware.

7.2 The flexibility of the micro-computer is often quoted as its major advantage over other control systems, but it has other major advantages. Because its functions are largely carried out in the software, the hardware count is minimised; thus the reliability of the system is much greater than analogue systems. The micro-computer is also used to assist in system fault diagnosis so that less skill is required by the maintainer.

7.3 The microcomputer has already proved itself in environments which are just as harsh as the marine one, over a number of years. The high reliability of the CPP mechanical systems is well proven (ref.1), and the increased reliability of microcomputer systems approaching 2 years MTBF rates, the reliability and integrity of microcomputer controlled CPP systems can be accepted.

7.4 The key to adaptable, high integrity digital systems is the use of well documented, modular software and hardware. These provide flexible systems at low first costs.

7.5 While the current systems being designed and manufactured jointly by HSDE and Lips do not reduce crew numbers, the systems considerably improve the operator performance. He can now concentrate much more on controlling and positioning his ship rather than on co-ordinating all the demand signals to his various propulsion devices. This will ease his task and make for safer ship operation.

7.6 The microcomputer as currently used in the systems described above has spare capacity which can be used to further enhance ship operation. Such items are synchronisation and synchrophasing of twin shafts to reduce vibration and noise. By precise control of the engines and propellers, fuel can be saved. With further experience, the overhaul intervals of engines and propulsion systems can be extended by using the microcomputer capability to calculate trends and predicate failure times.

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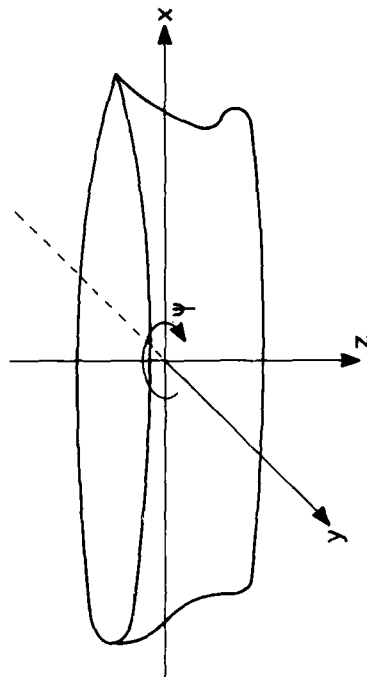


Fig. 1 Ship Co-ordinates

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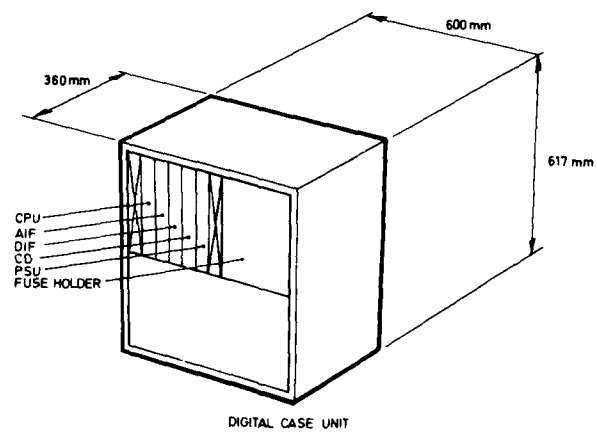
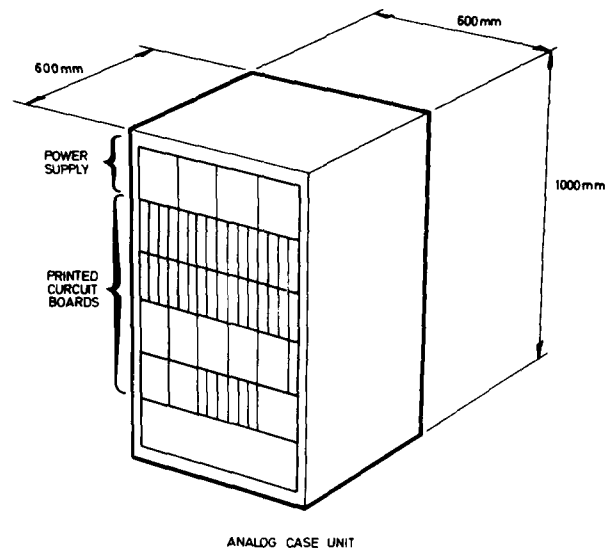


Fig. 2 Dimensions of Case Units

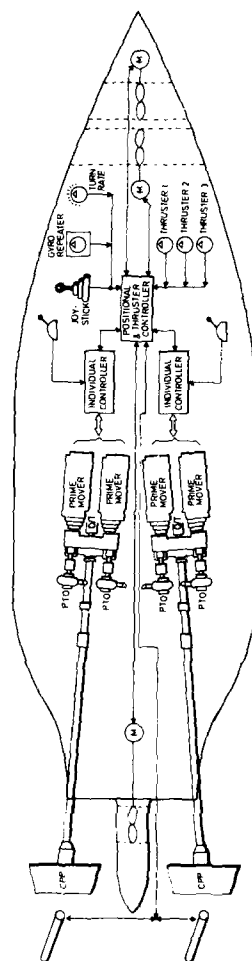


Fig. 3 Positional and Individual Controllers

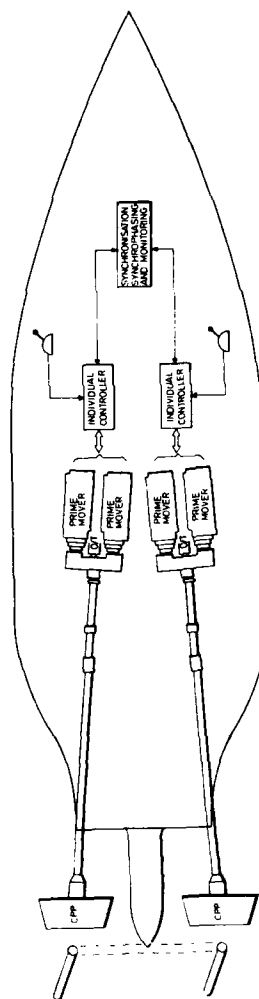
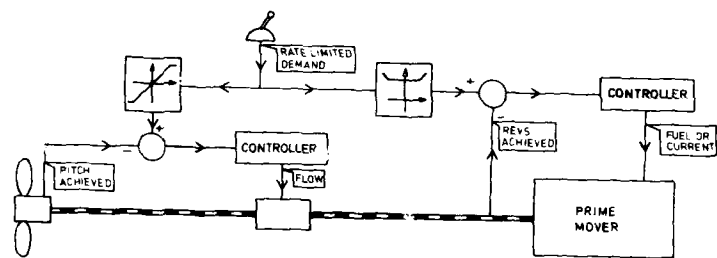
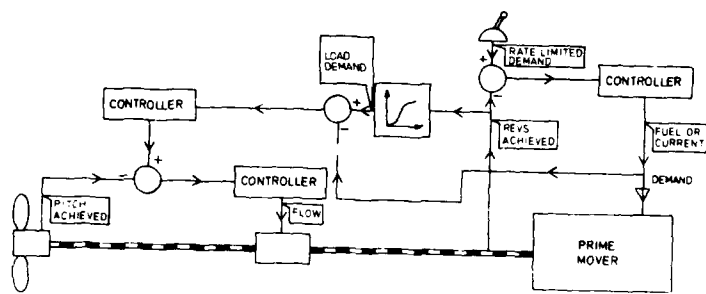


Fig. 4 Speed Control



(a) Scheduled Pitch and Revs Control . Continued - Control



(b) Independent Torque and Revs Control. Load - Control

Fig. 5 Basic Control Loops

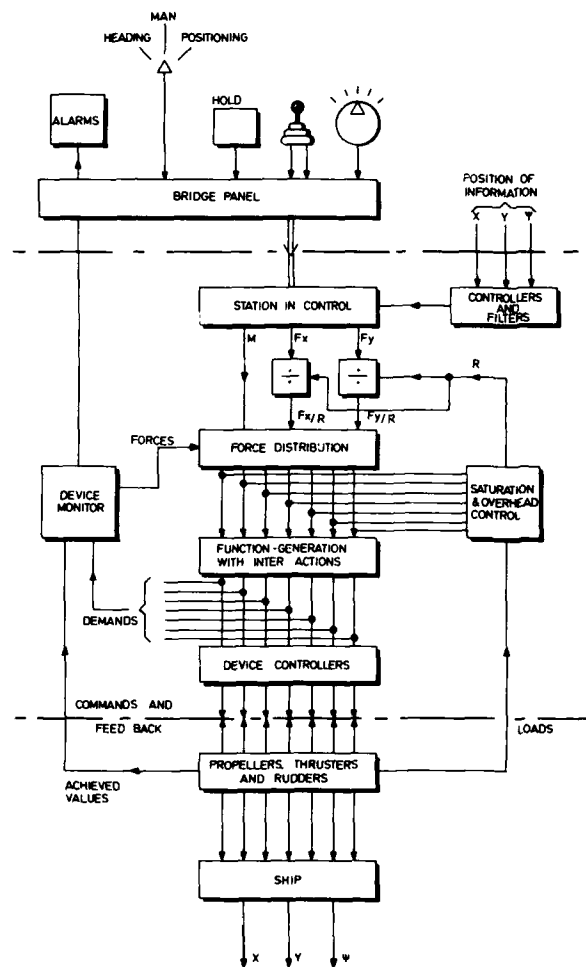


Fig. 6 Positional Control System

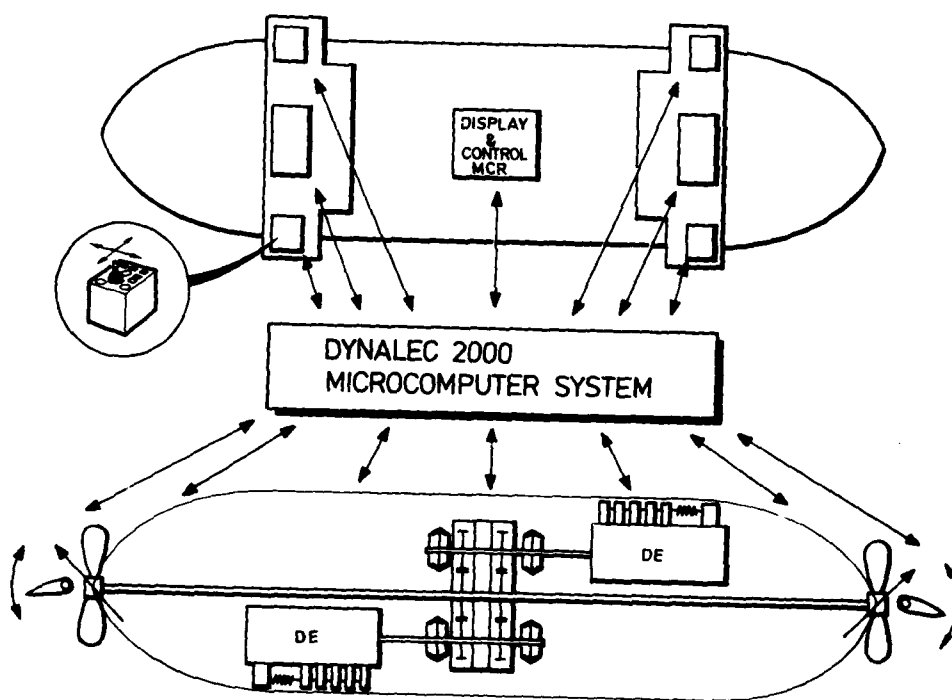


Fig. 7 Double Ended Ferry

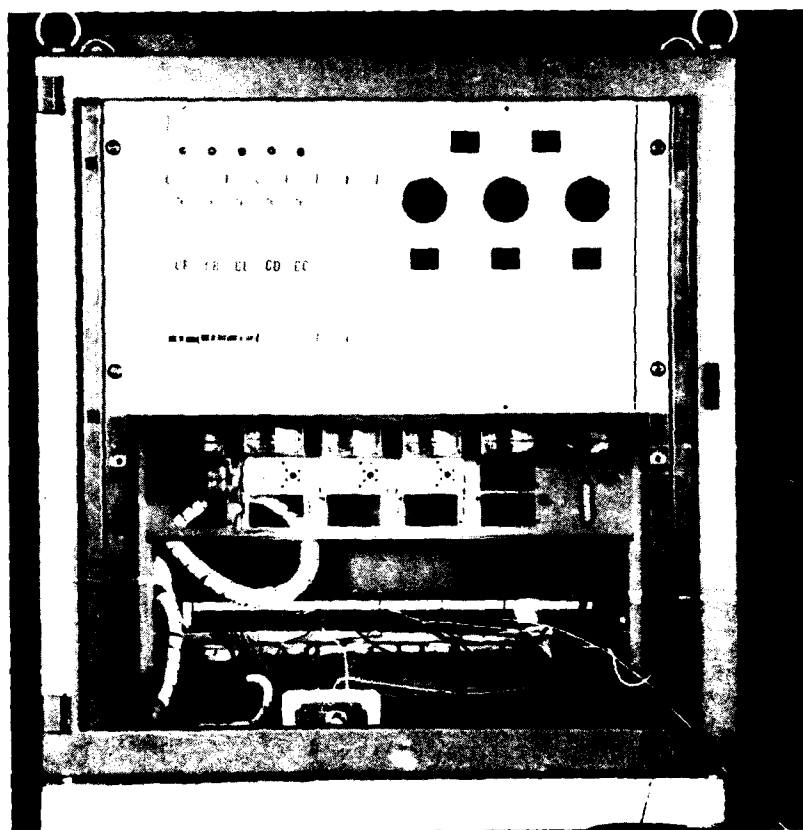


Fig. 8 Control System Cabinet and Rack

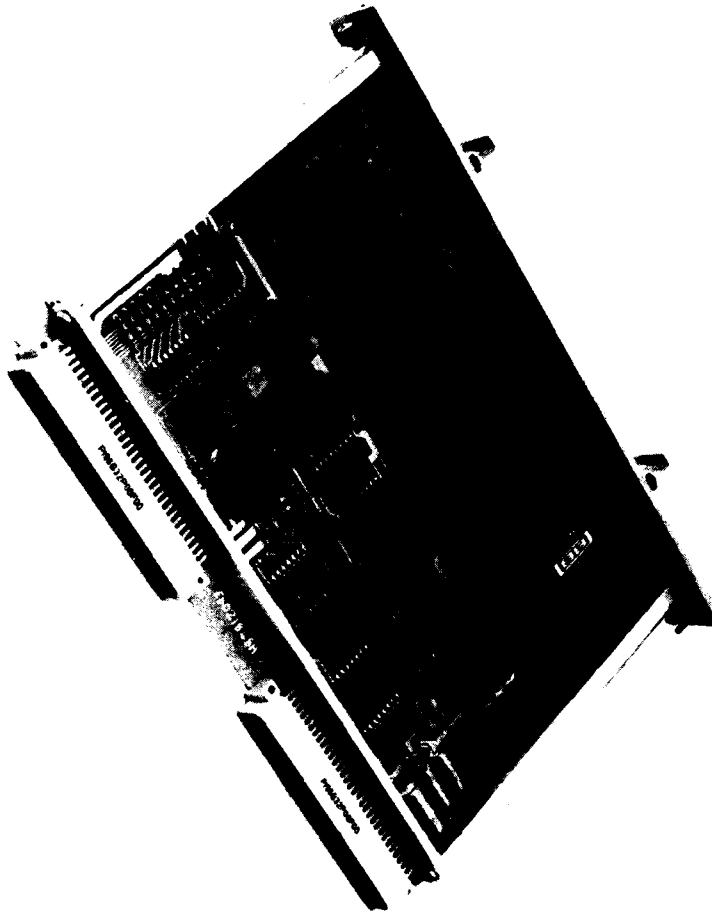


Fig. 9 Central Processing Unit

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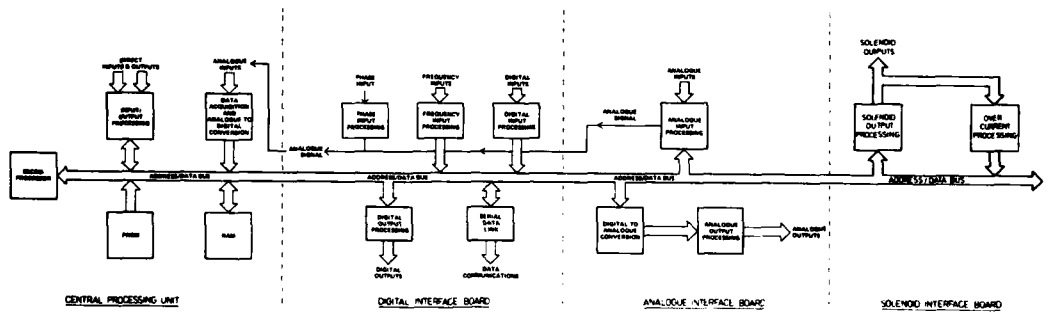


Fig. 10 System Architecture

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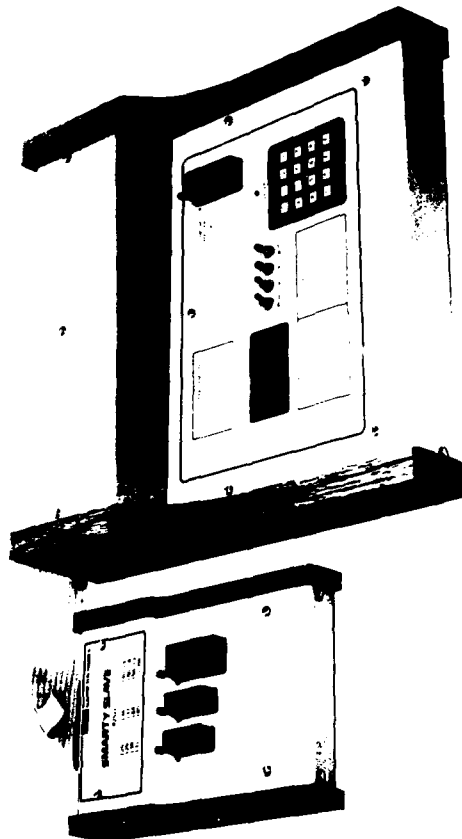


Fig. 11 PROM Interface Unit

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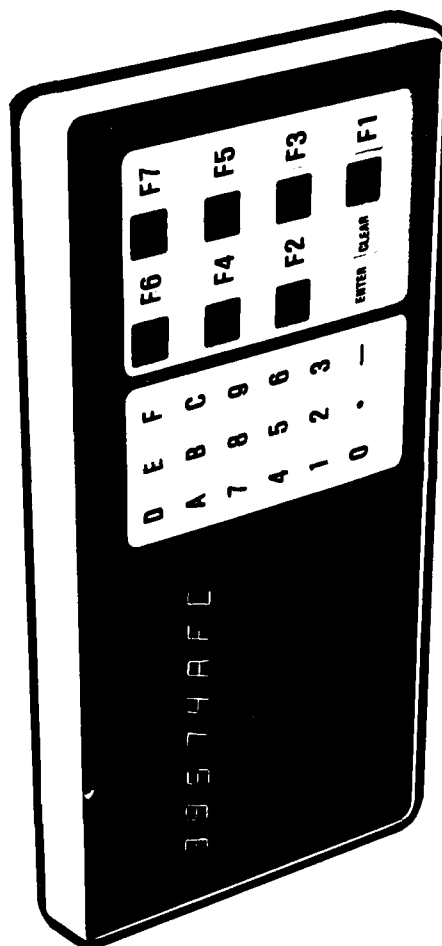
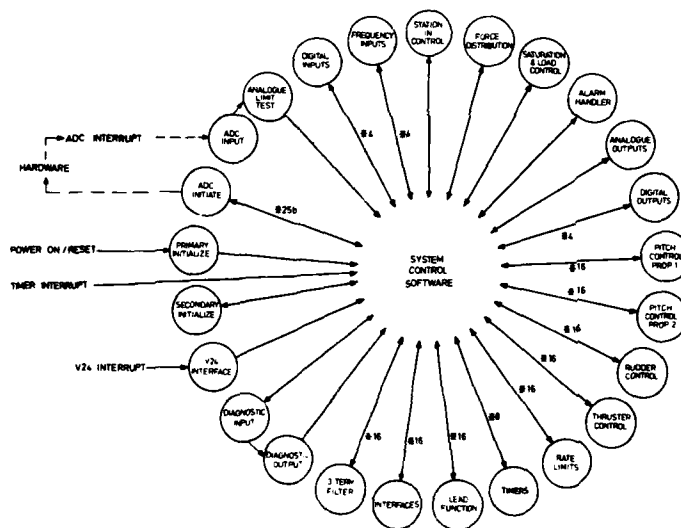


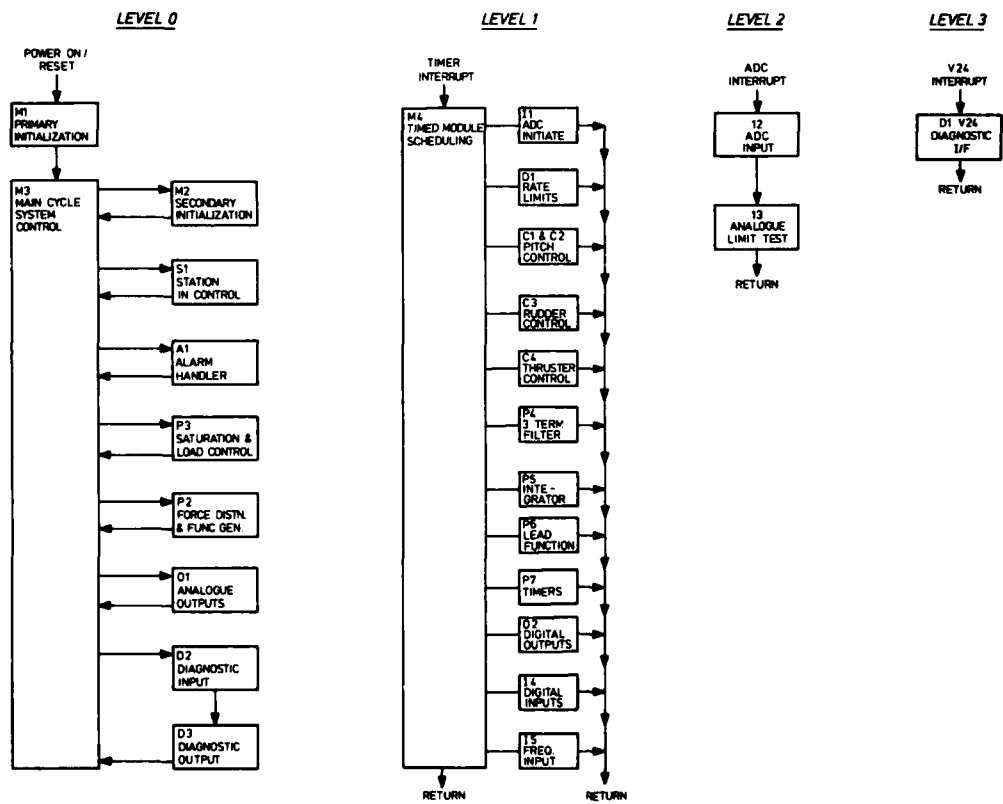
Fig. 12 Diagnostic Unit

Fig. 13 Modular Software



NOTE: STANDED ITEMS ARE CALLED ON THE BASIS INTERRUPT (DRIVEN) BY SYSTEM CONTROL SOFTWARE

Fig. 14 Lips-stick Operating Levels and Sequence of Procedures



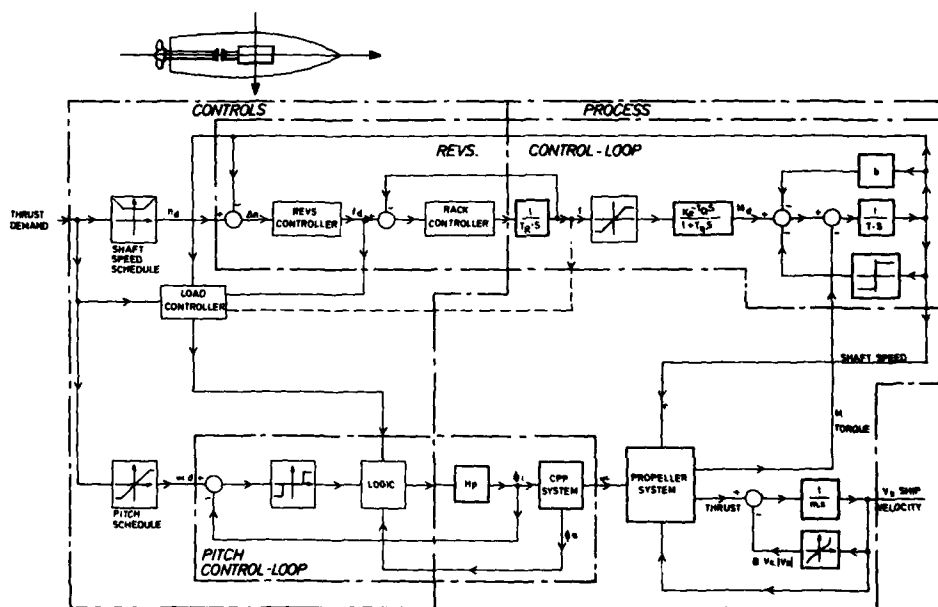


Fig. 15 Overall Control System

J2-27



THE INFLUENCE OF PARTIAL PLANT IGNORANCE, UNCONTROLLABLE
INPUTS AND SYSTEM CONSTRAINTS ON THE CHOICE OF AUTOPILOT
STRUCTURE FOR AUTOMATIC COURSE KEEPING

by C. S. Cox, Sunderland Polytechnic,
and G. Hunt, South Shields Marine and Technical College

ABSTRACT

The inability of autopilots with one degree of freedom to simultaneously minimise the effect of plant variations and satisfy desired plant response characteristics in the presence of system disturbances is highlighted. A two degree of freedom solution based on a minor-loop feedback strategy is advanced and the improved performance closely examined against the cost of a new complexity.

INTRODUCTION

The design of any control system is invariably a compromise based on the accuracy of your plant identification study, the inexactness of your knowledge of those disturbance effects deemed uncontrollable and the severity, nature and type of any constraints present. In addition, invariably the user requests the controller to be as simple as possible whilst in reality the complexity of the required feedback mechanism is strongly influenced by the nature of the overall objectives of the system. The result of this confusion is invariably an abundance of radically different solutions to what initially seemed to be the same problem.

One such problem which seems to have received much attention in the literature is that of automatic course keeping. This paper does not initially attempt to produce a new solution, but instead examines those areas the authors feel have most strongly shaped the current trends. The paper begins by looking at the classical approaches using Bode diagram (and/or root-locus plots). It then compares these strategies with the "quadratic cost" solutions. The extension of this latter work to examine solutions based on stochastic disturbances for those investigations where a regular sea characterisation is acceptable concludes the work.

PRELIMINARY THEORETICAL CONCEPTS

Let us consider initially the single-degree-of-freedom structure of Figure 1, where $F(s)$ represents the plant transfer function and $G(s)$ the adjustable controller transfer function.

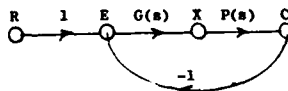


Figure 1. Single-Degree-Of-Freedom System.

$P(s)$ is assumed to have a fixed structure but its individual gains and time constants may vary with time. For this system we can easily show that

$$\frac{C(s)}{R(s)} = T(s) = \frac{G(s)P(s)}{F(s)} \quad \text{..... 1}$$

where the return difference, $F(s)$ is given by

$$F(s) = 1 + L(s) = 1 + G(s)P(s) \quad \text{..... 2}$$

Further, Horowitz^{1,2} has shown, for this case, that the system sensitivity to variations in $P(s)$ is given by the inverse of the return difference i.e.

$$S_P^T \triangleq \frac{\Delta T/T}{\Delta P/P} = \frac{1}{F(s)} = \frac{1}{1 + L(s)} = 1 - T(s) \quad \text{..... 3}$$

where $\Delta T = (T - T_0)$, $\Delta P = P - P_0$ and P_0 , T_0 and L_0 are the nominal plant, system and loop transfer functions respectively. Whilst $T(s)$ represents the system transfer function corresponding to $P(s)$.

The classical control specification results in shaping $G(s)P(s)$ to realise a desired $T(s)$. $T(s)$ is generally selected on the grounds of satisfactory steady-state and dynamic performance. Usually it is assumed that the plant parameters are fairly stable and do not vary too much or that the return difference is sufficiently large to assume the effects of any parameter change to be negligible. However, since only $G(s)$ is adjustable, it is impossible to independently realise $T(s)$ and $F(s)$ when this assumption is invalid. Fortunately all that is needed to achieve this independence is a structure with two-degrees-of-freedom¹. One suggestion could be the inclusion of an additional transfer function $H(s)$ as shown in Figure 2. The need for two independent transfer functions in the system and the corresponding additional design labour is one of the prices paid for the benefits of independence.

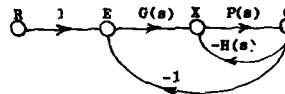


Figure 2. Two-Degree-of-Freedom System.

Finally the single-degree-of-freedom configuration also has an inherent weakness in its inability to satisfy a conventional specification and at the same time reject the influence of any external disturbance. For a disturbance D_1 at the input to $P(s)$ it is established that

$$\frac{C_{D_1}(s)}{D_1(s)} = T_{D_1}(s) = \frac{P(s)}{1 + L(s)} = P(s)(1 - T(s)) \quad \text{..... 4}$$

Since $P(s)$ is fixed, the choice for rejection is to make $[1 - T(s)]$ small for the important frequency range of $D(s)$. Obviously noise entering the system at other stations, including the input, must also be accounted for when choosing $T(s)$.

Let us now verify some of the above statements by examining a family of autopilot structures but initially let us consider the vehicle for our study.

THE SHIP AND STEERING GEAR TRANSFER FUNCTION

On perusing the literature one finds that a number of acceptable ship models have been advanced. They are however in general nonlinear and many of their parameters vary with sea-state, ship-speed, load and type of manoeuvre. It is intended here to use the well accepted Nomoto form^{3,4} of ships transfer as the basic model.

The ship to be used as our design vehicle is a 55,000 tonne liner (or containership) which is course stable. The steering engine is of a conventional form with an equivalent time constant T_e of 2.2 second. In order to maintain linear control the rudder angle should not exceed $\pm 5.7^\circ$ (this corresponds to maximum pump rate). The transfer function relating yaw rate to rudder movement is given by

$$\frac{\dot{\psi}}{\delta_0} = \frac{K(1 + sT_3)}{(1 + sT_1)(1 + sT_2)} \quad \dots\dots 5$$

where $K = 0.7909$, $T_1 = 627.3$, $T_2 = 4.5$ and $T_3 = 9.5$. Figure 3 is a block diagram of the ship steering system. The design problem is the choice of autopilot structure.

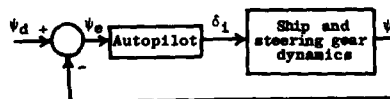


Figure 3. Single-Degree-Of-Freedom Course-Keeping System.

SINGLE-DEGREE-OF-FREEDOM STRATEGIES

(i) Autopilot with only Proportional Control

For this case the autopilot transfer function is given by

$$\frac{\delta_1}{\dot{\psi}_e} = K_r \quad \dots\dots 6$$

The frequency response of the ship plus steering gear dynamics is plotted in Figure 4 whilst Figure 5 shows the response of $\dot{\psi}$ and δ_0 (the rudder angle) to a step in $\dot{\psi}_d$ of A° for three values of K_r obtained from "quadratic cost" solutions to be discussed later. From these graphs we can ascertain the following

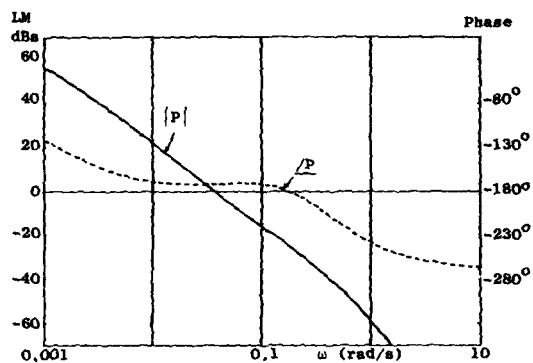


Figure 4. Frequency Response of Ship Plus Steering Gear

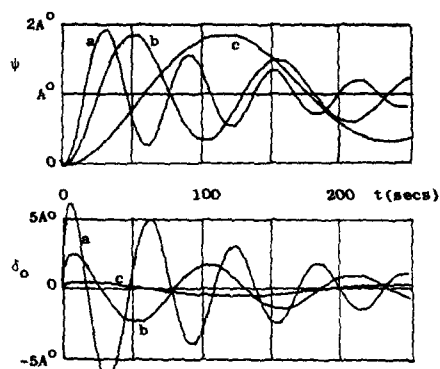


Figure 5. Response of Heading ψ and Rudder Angle δ_o to a Step In Demanded Heading ψ_d of 1° .
(a) $K_r = 7.07$ (b) $K_r = 2.75$ (c) $K_r = 0.574$

- (a) When $K_r > 17.8$ unstable operation will result.
- (b) The system is type 1.
- (c) The step responses confirm the Bode diagram in that stable but very oscillatory performance is predicted for $0.5742 \leq K_r \leq 7.072$.
- (d) Only $K_r = 7.072$ violates the $\delta_{o\max} = 5.7^\circ$ constraint on rudder angle for a 1° step, but for a 10° step only $K_r = 0.5742$ does not violate the constraint.
- (e) As K_r is reduced both the low frequency and high frequency performance is degraded.

- (f) System stability is most sensitive to parameter changes in T_2 and T_3 (actually a decrease in T_3 of less than 50% causes the system to go unstable).

Figure 6 shows a plot of $|S_p^T|$ corresponding to the definition of Equation 3. It is seen that at low frequencies the system is less sensitive to parameter variations as K_r increases, however there is a range of frequencies (corresponding to the vicinity of the gain cross-over frequency of the open-loop system) where the system sensitivity is worse than if no feedback were used. This is always the case for as Bode noted⁵ the integrated sensitivity function over all ω is zero.

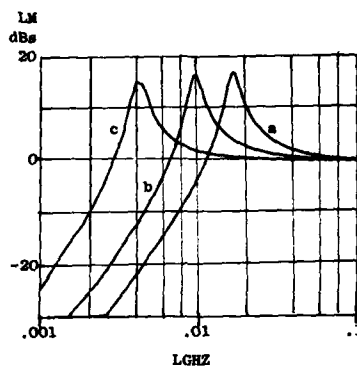


Figure 6. Plot of $20\log_{10} |S_p^T|$ Versus Frequency.

(a) $K_r = 7.07$ (b) $K_r = 2.75$ (c) $K_r = 0.574$

The noise response at the plant input to noise appearing at C is given by

$$\frac{X}{N} = \frac{-G}{1+L} \quad \dots 7$$

In the range where $|L(j\omega)| < 1$

$$\frac{X}{N} = -G = -K_r \quad \dots 8$$

Obviously when $K_r > 1$ the noise is amplified often resulting in plant input saturation. Let us now consider the implications of replacing proportional action by three-term-action.

(ii) Autopilot With Three Term Action

Most commercial autopilots incorporate three term action. For our simulation work the transfer function of the autopilot has the form of equation 9 and represents the Decca Arcus system i.e.

$$\frac{\delta_i}{\psi_e} = \frac{K_R[1 + sT_{ph}][1 + sK_{cr}T_{cr}]}{sT_{ph}[1 + sT_d]} \quad \dots\dots 9$$

Immediately it is observed that a much more complicated control strategy is possible since in theory all of the parameters are available for adjustment. In practice, however, it is usual to fix T_{ph} , T_{cr} (say) and T_d leaving the pilot the task of achieving suitable control by varying K_R (the rudder gain) and K_{cr} (the counter rudder gain). In addition a further constraint is imposed in that the values of K_R and K_{cr} are restricted, in this case, as follows

$$0.5 \leq K_R \leq 3; \quad 1 \leq K_{cr} \leq 8 \quad \dots\dots 10$$

Here, T_{cr} and T_d are selected as suggested by Bech⁶, whilst T_{ph} is the smallest value which did not produce a conditionally stable closed-loop system.

The frequency response of the ship, steering gear and autopilot corresponding to extreme pairings of K_R and K_{cr} (i.e. 0.5 and 1, and 3 and 8 respectively) is plotted in Figure 7, whilst Figure 8 presents the response of ψ and δ_o to a step in ψ_d of A° for three different pairings of K_R and K_{cr} . From these graphs we can make the following comparisons with pure proportional control

- (a) The system is type 2 consequently an improved tracking capability is predicted.
- (b) The step responses confirm the Bode diagram prediction that the relative stability is improved as K_{cr} is increased, as is the speed of response with increasing K_R .
- (c) When $K_R = 3$, $K_{cr} = 8$ the rudder angle constraint is violated for any $\psi_d > 1^\circ$, whilst a $\psi_d = 10^\circ$ requires a maximum rudder angle deviation of approximately 120° . Since the rudder itself is constrained to $\pm 37^\circ$ this example highlights one of the problems of a design based only on output/input information.

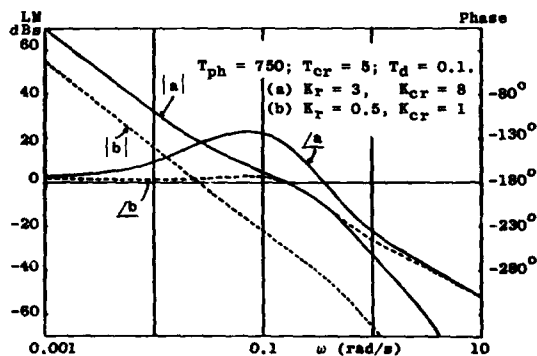


Figure 7. Open-Loop Frequency Response of Ship, Steering Gear and Three-Term Autopilot

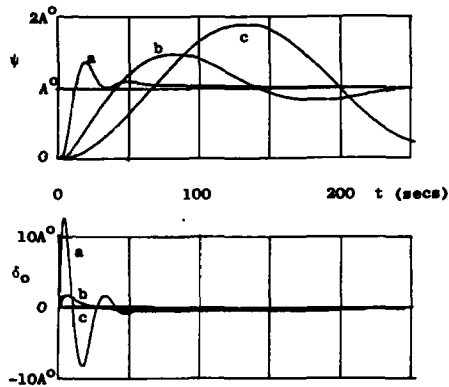


Figure 8. Response of Heading ψ and Rudder Angle δ_0 to a Step in Demanded Heading ψ_d of A° .
 (a) $K_R = 3$, $K_{CR} = 8$ (b) $K_R = 1$, $K_{CR} = 4$
 (c) $K_R = 0.5$, $K_{CR} = 1$

Figure 9 is a plot of $|S_p^T|$. Note that the closed-loop response in all cases is not nearly so sensitive to parameter variations in the critical range specified by $1/T_2$ and $1/T_3$ as for the case when only proportional control is used.

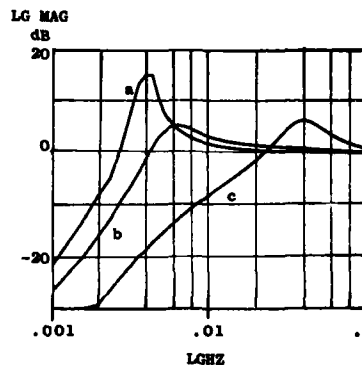


Figure 9. Plot of $20 \log_{10} |S_p^T|$ Versus Frequency.
 (a) $K_R = 0.5$, $K_{CR} = 1$; (b) $K_R = 1$, $K_{CR} = 4$; (c) $K_R = 3$, $K_{CR} = 8$.

Finally, the possibility of input saturation due to the presence of system noise increases as both the values of K_R and K_{CR} are increased.

TWO-DEGREE-OF-FREEDOM STRATEGIES
A MINOR-LOOP FEEDBACK INTERPRETATION

The previous section confirmed that single-degree-of-freedom configurations (even quite sophisticated ones) in general are unable to satisfy simultaneously a desired closed-loop response as specified by $T(s)$ whilst at the same time satisfying tolerances due to parameter variations and/or disturbances acting on the ship plus constraints on rudder angle. A large family of two-degree-of-freedom configurations have been presented in the literature. However, for the special class of problems where the plant has only two access points (the input and output) and if access to the output is only via the plant (as it is in this case) then none of the structures¹ can achieve any more than any of the others. The autopilots to be presented here are based on the familiar minor-loop feedback configuration of Figure 2. For these situations we can easily show that

$$\frac{C(s)}{R(s)} = T(s) = \frac{G(s)P(s)}{F(s)} \quad \text{..... 11}$$

where

$$F(s) = 1 + L(s) = 1 + P(s)[G(s) + H(s)] \quad \text{..... 12}$$

and

$$S_P^T = \frac{1}{1 + L(s)} \quad \text{..... 13}$$

The basic design strategy is to use equation 13 to determine the "form" of $L(s)$ to satisfy a given S_P^T ; then using $L(s)$ together with $T(s)$ determine $G(s)$ and $H(s)$ from equations 11 and 12. The configuration we have chosen is not the simplest one to demonstrate the design philosophy (because of the additive form of $G(s)$ and $H(s)$ in equation 12). However, since the purpose of the section is not principally one of design but mainly one of illustrating the advantages and problems of two-degree-of-freedom structures, this is not considered a drawback.

The open-loop transfer function for the system of Figure 2 is given by

$$\frac{C(s) - R(s)}{C(s)} = \frac{G(s)P(s)}{1 + P(s)H(s)} \quad \text{..... 14}$$

It follows using equation 14 that we can shape the open-loop response by suitable choice of $G(s)$ and $H(s)$. In order to make an intelligent choice of $G(s)$ and $H(s)$ we note that if

$$P(s)H(s) \ll 1 \text{ then } \frac{C(s) - R(s)}{C(s)} \approx G(s)P(s) \quad \dots\dots 15$$

$$\text{whilst if } P(s)H(s) \gg 1 \text{ then } \frac{C(s) - R(s)}{C(s)} \approx \frac{G(s)}{H(s)} \quad \dots\dots 16$$

Since both of these relationships are products, and if Bode diagram co-ordinates are used, the effect of $G(s)$ can be neglected initially, then superimposed later. This is the strategy to be followed here.

(i) Autopilot With Proportional Gain and Velocity Feedback

In an attempt to reduce the oscillatory behaviour of the system response a common strategy is to incorporate a negative feedback loop dependent on the rate of change of the controlled variable. In the notation of Figure 2 this is achieved with

$$G(s) = K_p \quad \text{and} \quad H(s) = sT_s \quad \dots\dots 17$$

The effect of increasing T_s (with $K_p = 1$) on the open-loop response is clearly seen in Figure 10. The step response behaviour of Figure 11 confirms the Bode diagram results in that a much more heavily damped response is obtained as T_s is increased. The penalty paid for this improvement is a degradation in the low frequency performance.

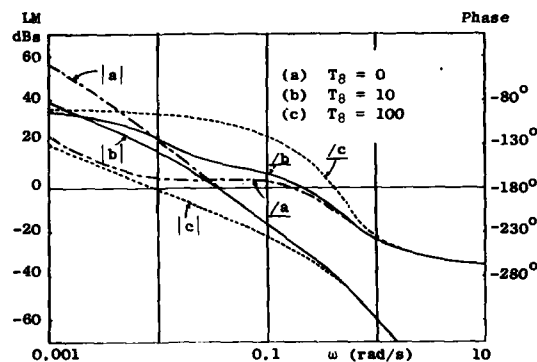


Figure 10. Open-Loop Frequency Response With Velocity Feedback Present and $K_p = 1$.

The peak sensitivity is found to be reduced by increasing T_s but, as expected, the low frequency sensitivity is not as good as the uncompensated system (see Figure 12).

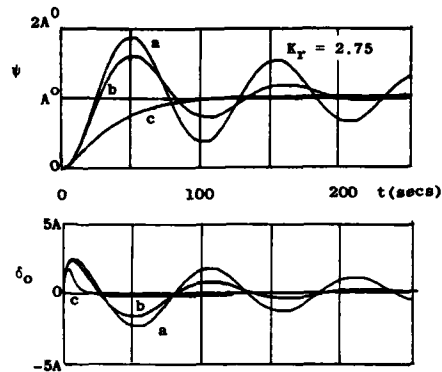


Figure 11. Response of Heading ψ and Rudder Angle δ_0 to a Step in Demanded Heading ψ_d of A° .
 (a) $T_8 = 0$; (b) $T_8 = 10$; (c) $T_8 = 100$

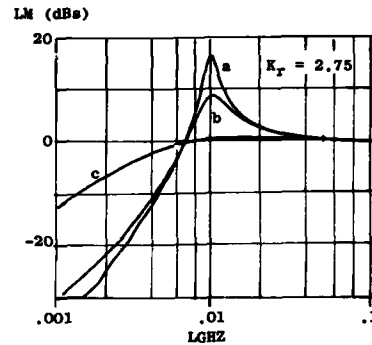


Figure 12. Plot of $20 \log_{10} |S_p^T|$ Versus Frequency.
 (a) $T_8 = 0$; (b) $T_8 = 10$; (c) $T_8 = 100$

(ii) Autopilot With Proportional Gain and Network Feedback

To overcome the problem of low frequency degradation a common approach is to construct a suitable $H(j\omega)$ function on the Bode diagram. The technique is to draw the desired $1/H(j\omega)$ curve below the $P(j\omega)$ curve in order to satisfy a "good" phase margin condition together with an acceptable closed loop bandwidth. The remaining structure is then chosen according to the particular application. Figure 13 shows the results of such a strategy which realised a feedback transfer function of the form

$$H(s) = \frac{s^2 T_8 (1 + sT_5)}{(1 + sT_6)(1 + sT_7)}$$

..... 18

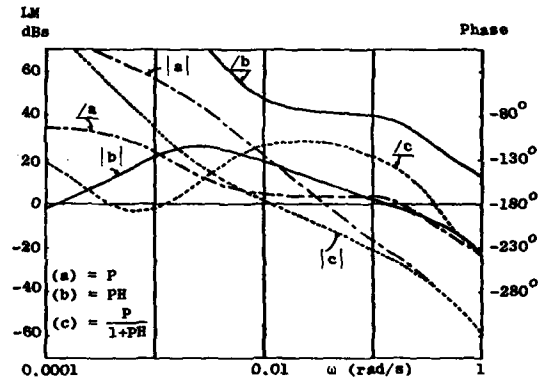


Figure 13. Open-Loop Frequency Response With Network Feedback and $K_r = 1$.

The design shown has an ω_{go} equal to the velocity feedback case with $T_8 = 100$. Again it is assumed that $K_r = 1$; the effect of K_r can of course be easily superimposed. Figures 14 and 15 show the step response behaviour and the closed-loop sensitivity. As expected, there is little difference from the velocity feedback case, but, at frequencies below 0.001 rad/s then sensitivity is much improved for this latter case as is the normal low frequency performance. Note however that some redesign may be required (as in this case) to avoid a conditionally stable system.

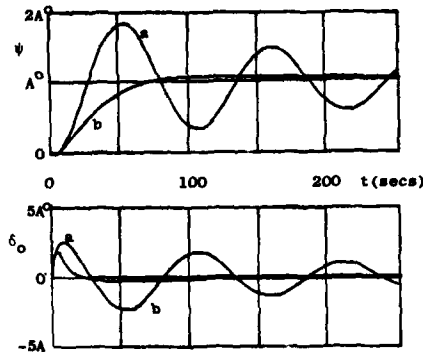


Figure 14. Response of Heading ψ and Rudder Angle δ_o to a Step In Demanded Heading ψ_d of A° .
(a) Without network; (b) With network.

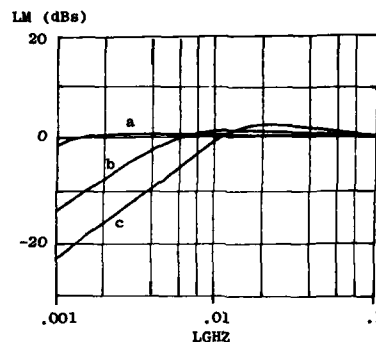


Figure 15. Plot of $20 \log_{10} |S_P^T|$ Versus Frequency.
(a) $K_r = 0.574$; (b) $K_r = 2.75$; (c) $K_r = 7.07$

(iii) Autopilot with Three-Term-Action and Velocity Feedback

For this structure, $G(s)$ is characterised by equation 9, whilst $H(s) = sT_8$. Figure 16 shows that as T_8 is increased the heading response becomes much less oscillatory but peak rudder movement is hardly influenced. Again peak sensitivity is reduced but low frequency sensitivity is inferior when compared with the uncompensated system (see Figure 17).

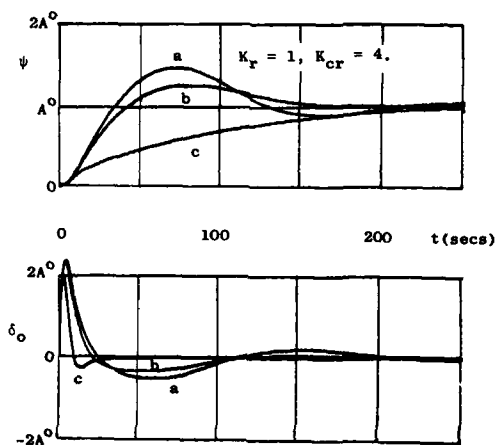


Figure 16. Response of Heading ψ and Rudder Angle δ_o to a Step in Demanded Heading ψ_d of A° .
(a) $T_8 = 0$; (b) $T_8 = 10$; (c) $T_8 = 100$

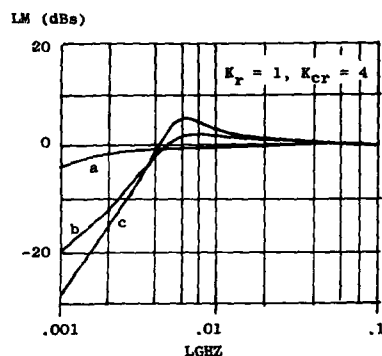


Figure 17. Plot of $20 \log_{10} |S_p^T|$ Versus Frequency.

(a) $T_8 = 100$; (b) $T_8 = 10$; (c) $T_8 = 0$.

(iv) Autopilot With Three-Term-Action Plus Network Feedback

For this structure, $G(s)$ is characterised by equation 9 and $H(s)$ is characterised by equation 18. Low frequency performance and sensitivity is again very much better than for just velocity feedback but there is very little difference in the step response behaviour when compared with the previous case when $T_8 = 100$.

OPTIMAL AUTOPILOTS

Once a structure is considered satisfactory the analyst is never happy until he has selected the individual components to give "optimal performance". The usual interpretation of "optimal performance" is a performance which maximises or minimises some form of quadratic objective function principally selected because of its nice analytic properties. The cost to be considered here is the familiar

$$\int_0^{\infty} (\psi_e^2 + \lambda \delta_0^2) dt \quad \dots 19$$

first suggested by Koyama⁷ and subsequently used by many investigators. The choice of λ has been shown⁸ to depend on whether the cost function is intended to minimise either time on voyage or alternatively to minimise fuel consumption on the voyage. However, if $\lambda = 0$, then there is no penalty on the rudder angle movement and its magnitude will be very large. From the previous sections one of the main problems has been the continual violation of the constraint imposed on rudder angle. Consequently, in this problem, to try and ensure linear control behaviour, $\lambda \gg 1$ has normally to be employed. Finally the optimisation algorithm used is based on a direct method utilising the gradient algorithm.⁹ The actual algorithm is due to Hasdorff¹⁰ and is based on a conjugate gradient descent strategy. The algorithm is a "time based" algorithm and whilst it has worked extremely well for a number of other control problems, it did not perform as efficiently here.

(i) A state variable feedback strategy

The principal requirements of the algorithm used were that we are able to evaluate the functional itself and the gradient of the functional in the region where the minimum is sought. By choosing the structure of the controller a priori, the design problem becomes one of the determination of the proper choice of controller parameters i.e. parameter optimisation.

The system dynamics are assumed to be described by a set of first order differential equations of the form

$$\dot{x} = f(x(t), a); \quad x(t_0) = x_0 \quad \dots 20$$

where a is an i^{th} dimensional vector, $a \in E^i$ i.e. a is a set of i parameters (namely K_r , K_{cr} , T_{cr} etc.). The control problem, is to determine the vector of parameters a which minimise the cost function

$$J[a] = \phi[x(t_f, a)] \quad \dots 21$$

subject to equation 20. In using equation 21 an important consideration is the choice of the time interval $[t_0, t_f]$. The usual rule is to choose t_f so that

$$t_f - t_0 \geq k\tau \quad \dots 22$$

where τ is the largest time constant of the system and k is generally in the range 3-5. This assumes that the system is in the steady-state by the final instant t_f .

The expression for the gradient vector¹⁰ is

$$g = \int_{t_0}^{t_f} f_a^T z(t) dt \quad \dots 23$$

where $z(t)$ is the solution to the adjoint system.

$$\dot{z}(t) = -f_x^T z(t); \quad z(t_f) = \nabla_x \phi[x(t_f, a)] \quad \dots 24$$

Hence using the value of the gradient computed from equation 23 the optimisation algorithm determines the new a and hence minimises the cost function.

It has been found from operational experience that the computational time is extremely long because of the spread of the eigenvalues (10,000:1) plus the large value associated with the longest time constant ($\approx 1,000$ seconds). Normally a good starting

point helped the algorithm convergence rate but the shallow nature of the cost surface in some cases still caused long computational times. Sensible results were obtained for three different choices of λ for the proportional only controller. Whilst for the three term controller case the results suggested with an increasing weighting on the rudder, $K_r \rightarrow 0.5$ and $K_{cr} \rightarrow 8$ (the constrained values). For the case when proportional control and velocity feedback were present the initial studies were for $\lambda = 0$ and 0.05 . The tendency of the algorithm was to drive both K_r and T_s towards very large values. Finally for two-term control plus velocity feedback the algorithm continually sought a negative gain for the integral action.

As a consequence of the above an alternative strategy using Parseval's Theorem was investigated.

(ii) A frequency domain strategy

Clarke¹¹ has shown that the above problem can be transferred to the frequency domain using Parseval's Theorem. The resulting integrals can be rapidly evaluated using an efficient recursive algorithm by Astrom.¹² The disadvantage of this approach is that we can not easily generate a relationship equivalent to equation 23 in the frequency domain. However, a minimum can be found merely by examining the computed level curves, although this can be a time consuming affair especially if more than one parameter is varied. One of the main advantages of the frequency domain approach is the ease with which the strategy can be extended to cover the case when stochastic disturbances (such as sea-states) are being considered.

CONCLUDING REMARKS

The paper demonstrates the influence that partial plant ignorance, noise influences and constraints have on autopilot performance. It is suggested that properly designed two degree of freedom structures will in general give improved performance. The authors are still looking into the "quadratic-cost" solutions and further work into the effects of the differing sea-state characterisations is being pursued. It is hoped to build into the quadratic cost a factor relating to system sensitivity, to this end a suggestion by Burzio and Siljak¹³ seems worth investigating.

ACKNOWLEDGEMENTS

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**"THE IMPACT OF GAS TURBINE CONTROL SYSTEMS' TECHNOLOGY
ON U.S. NAVY PERSONNEL AND TRAINING"**
by E.F.M. McGonagle NAVSEA (USA)

I. INTRODUCTION

In this presentation, I will discuss briefly the advent of a new era for the U.S. Navy - namely that of gas turbine propulsion - and how the Navy has dealt with the personnel and training demands that this new technology has brought with it.

I will illustrate the impact of this new technology on personnel and training requirements by comparing the manning for control systems on an older steam propulsion ship with that of a newer gas turbine powered ship of similar size and capability. Here I will also address the engineering advances of the gas turbine control systems over the steam control systems.

I will conclude by reiterating the major points made in the presentation as well as some final judgments on the subject.

II. BACKGROUND

In 1974, when the U.S. Navy began building its first two major gas turbine powered ship classes - DD-963 and PHM-1 - it had very little prior gas turbine experience to go on. This experience consisted mainly of the PG-84 class of Patrol Gunboats, which combined diesel with gas turbine propulsion, along with Naval Aviation's experience with gas turbine engines.

The U.S. Navy found itself in the position of building 30 DD-963 Class destroyers and 6 PHMs (Patrol Combatant - Missile (Hydrofoil)) and had virtually no backlog of sailors on hand with gas turbine know-how. This meant a new type of sailor had to be trained with gas turbine engine and controls systems operation and maintenance skills. In fact, many new gas turbine technicians had to be trained since the U.S. Navy was making a commitment to gas turbine propulsion to the extent that, by the mid-1980s, one quarter of the surface fleet would be gas turbine propelled and by the mid-1990s approximately 50% of U.S. surface ships would be gas turbine driven.⁽¹⁾ It is estimated that by 1985, 2500 gas turbine-trained personnel will be required to man gas turbine ships.⁽²⁾

The U.S. Navy's commitment to gas turbine propulsion naturally was dictated by its technological advantages over steam propulsion in such areas as reduced space and weight, lack of complexity, ease of engine replacement, reduced maintenance, and overall reduced cost to mention only some of the advantages. Not the least of the reasons for switching to a more automated gas turbine propulsion system was the reduced manning level which would result. For example, the Engineering Department of the DD-963 class destroyer requires 2 officers and 54 enlisted personnel compared with 4 officers and 105 enlisted of the CG-26, its steam propelled counterpart. This is a reduction in personnel by nearly one half.

This reduced manning level of gas turbine ships fell into step with Navy policy which, during the mid-1970's, was taking a hard look at its dwindling manpower reserves as well as its rising manpower costs. For example, in FY 76, 54.1 percent of the total Department of Defense budget was identified as personnel costs as opposed to 41.8 percent so identified in FY 68.⁽³⁾ This was approximately a 12 percent increase over an eight year period.

The U.S Navy began tackling the problem of creating a new gas turbine sailor by establishing a Gas Turbine Technician (GS) rating in 1972. The implementation of this rating was deferred, however, because it was felt that cross training an individual in both the mechanical and electrical aspects of gas turbine systems was not feasible and that such training would constitute too long a training pipeline. It was also agreed that implementation of the GS rating would wait until some time after DD-963 contractor training was completed in order to minimize disruption during this crucial initial training period.

Instead of the GS rating, the Navy went with existing ratings - Engineman (EN), Electrician's Mate (EM), and Interior Communications Electrician (IC) - with Navy Enlisted Classification (NEC) codes to denote areas of gas turbine specialization. For example, with respect to the control systems operator and maintenance personnel only, we see the following:

TABLE 1

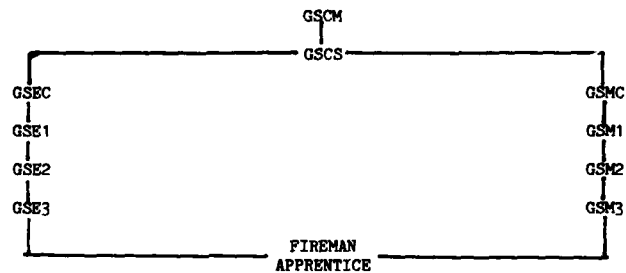
<u>RATING</u>	<u>NEC</u>	<u>TITLE</u>
Engineman (EN)	4111	Machinery Control System Operator
Electrician's Mate (EM)	4111	Machinery Control System Operator
Interior Communications Electrician (IC)	4115	Gas Turbine Controls Maintenance Technician

Once a sailor received gas turbine training and was given a gas turbine related NEC such as those shown in Table 1, he would remain exclusively in the gas turbine area. This was known as "closed loop" detailing.

The rating and NEC structure shown in the Table proved to be a successful approach to providing the personnel and training requirements of these first gas turbine ships. However, as time went on, gas turbine-trained personnel became more and more impatient about having their own identity i.e. their own Gas Turbine rating. They rightly felt that their sophisticated operator and maintainer skills deserved the recognition of a separate rating rather than an NEC especially since many less demanding fields had their own ratings. Besides, the growing number of gas turbine personnel within the EN, EM, and IC ratings was beginning to raise personnel advancement problems. For example, with respect to the Advancement-In-Rating exam, how was the EN who was kept exclusively in the gas turbine field to compete on an exam geared to diesel and steam systems. This problem is typical of those created by the impact of the new gas turbine technology on Navy personnel and training.

In 1978, the implementation of the GS rating was again reviewed and the decision finally made to adopt the Gas Turbine Technician (GS) rating and establish within that rating GSE (Electrical) and GSM (Mechanical) Service Ratings. The rating structure looked like this:

TABLE 2



The conversion from the previous ratings and NECs to the GS service ratings looked like this:

TABLE 3

<u>Pre-GS Rating</u>	<u>NEC</u>	<u>GS Rating</u>
Engineman (EN) (DD-963 Class Machinery Control System Operator)	4111	GSM 4111 (DD-963 Class Gas Turbine Operator and Mechanical Maintenance Technician)
Electrician's Mate (EM) (DD-963 Class Electrical Equipment Technician)	4112	GSE 4115 (DD-963 Class Gas Turbine Electrical Maintenance Technician)
Interior Communications Electrician (IC) (DD-963 Class Gas Turbine Controls Maintenance Technician)	4115	GSE 4115 (DD-963 Gas Turbine Electrical Maintenance Technician)
Electricians Mate (EM) (DD-963 Class Gas Turbine Controls Maintenance Technician)	4115	

III. COMPARATIVE MANNING AND TRAINING ANALYSIS OF THE USS SPRUANCE (DD-963)
(GAS TURBINE PROPULSION) AND THE USS BELKNAP (CG-26) (STEAM PROPULSION)

At this point I would like to compare two ships, the USS SPRUANCE (DD-963) and the USS BELKNAP (CG-26), which are physically similar but one of which is older and steam propelled while the other represents a more modern state-of-the-art and is gas turbine propelled. By making this comparison, I want to show the impact which advanced technology in gas turbine propulsion control systems has had on personnel and training. Below is a table comparing certain prominent characteristics of each type ship.

TABLE 3

	USS BELKNAP (CG-26)	USS SPRUANCE (DD-963)
Length -	547'	563'
Beam -	54 3/4'	55'
Draft -	28 3/4'	29'
Propulsion -	steam turbines; 85,000 SHP; 2 shafts	gas turbines; 80,000 SHP; 2 shafts
Speed -	33 knots	33 knots
Range -	7100 n. miles at 20 knots	6000 n. miles at 20 knots

After noting the physical similarities of the two ships, it is interesting to compare the manning of the engineering spaces under Condition III - Wartime Cruising Readiness.

The manning of the USS BELKNAP looks like this:

TABLE 4

CG-26

Engineering Control

Condition III

<u>WATCH STATION TITLE</u>	<u>DIV.</u>	<u>RATE/RATING</u>	<u>NEC</u>
<u>Engine Rm. Fwd.</u>			
Engineering Officer of the Watch (EOOW)	A	MMC	4518
	B	BTC	
	M	MMC	
Machinist Mate of the Watch (MMOW)	M	MM2	
Upper Levelman/Evap/Generator	M	MM2	
Throttleman (1JV)	M	MM3	
Lower Levelman	M	MM3	
N1-4			

<u>WATCH STATION TITLE</u>	<u>DIV.</u>	<u>RATE/RATING</u>	<u>NEC</u>
Switchboard Oper.	E	EM3	
Log Recorder/Messenger	M	MMFN	
<u>Engine Rm. Aft.</u>			
Machinist Mate of the Watch (MMOW)	M	MM1	
Upper Level/Evap/Generator	M	MM2	
Throttleman (1JV)	M	MM3	
Lower Levelman	M	MM3	
Log Recorder/Messenger	M	MMFN	
<u>Fire Rm. Fwd.</u>			
Boiler Technician of the Watch (BTOW)	B	BT2	4518
Console Operator	B	BT2	4533
Upper Levelman	B	BT3	
Lower Levelman	B	BT3	
Log Recorder/Messenger	B	BTFN	
<u>Fire Rm. Aft.</u>			
Boiler Technician of the Watch (BTOW)	B	BT2	4518
Console Oper.	B	BT2	4533
Upper Levelman	B	BT3	
Lower Levelman	B	BT3	
Log Recorder/Messenger	B	BTFN	
<u>Damage Control Central</u>			
Damage Control Supervisor	R	HT3	
Sounding & Security Watch	R	HTFN	
TOTAL WATCHSTANDERS = 24			

Table 5 below shows the engineering watch stations of the DD-953, again under the Condition III state of manning readiness.

TABLE 5

DD-963

<u>Engineering Control</u>	<u>Condition III</u>		
<u>WATCH STATION TITLE</u>	<u>DIV.</u>	<u>RATE/RATING</u>	<u>NEC</u>
<u>Central Control Station</u>			
Engineering Officer of the Watch (EOOW)	MP N1-5	GSCM/GSMC/GSEC	411X

<u>WATCH STATION TITLE</u>	<u>DIV.</u>	<u>RATE/RATING</u>	<u>NEC</u>
Prop/Aux. Control Console Oper.	MP	GSM2	4110
Elect. Plant Control Console Oper.	MP	GSE3	4110
Equip. Monitor/Repair	MP	GSE3	4110
 <u>Engine Rm. Fwd. Local Operating Station (LOS)</u>			
Prop LOS Oper.	MP	GSM3	4110
 <u>Engine Rm. Aft. Local Operating Station (LOS)</u>			
Prop LOS Oper.	MP	GSM3	4110
 <u>Damage Control Central</u>			
Fuel Sys Control Console Oper.	R	HT3	
TOTAL WATCHSTANDERS = <u>7</u>			

Having compared the manning between the two ships and found the steam propulsion plant to require over three times as many personnel as the gas turbine plant, let us now take a look at the training pipelines required for the personnel of each ship (see Tables 6 and 7).

What is immediately apparent in the tables is the difference in the length of training for Boiler Technicians and Machinists Mates as compared to the Gas Turbine Technician. This is to be expected, of course, since the gas turbine system is highly automated and involves a great deal more electronics. This fact can be seen particularly in the GSE and GSM operator courses which take a total of five and seven weeks respectively as compared to three weeks in the case of the BT Console Operator.

The same point is evident to an even greater extent on the maintenance side where the GSE, who performs control systems' maintenance, receives 28 weeks of maintenance training - 16 weeks of which is on Engineering Control and Surveillance System (ECSS) alone. In contrast, maintenance training for the MM and BT is six and seven weeks respectively.

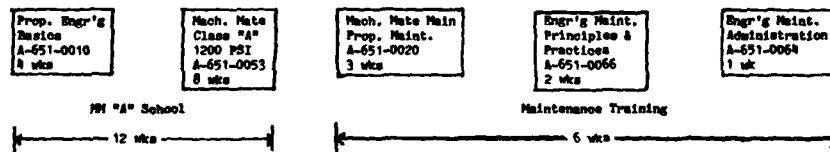
IV. CONCLUSION

In conclusion, this paper is about the U.S. Navy's efforts in the personnel and training area to catch up with technology. To do this, the Navy created a new gas turbine sailor who might receive as much as 50 weeks of highly sophisticated training compared to a maximum of 20 weeks for his steam counterpart. This new sailor would likely spend his watch sitting at a Central Control Station following the progress of the propulsion plant by monitoring display panels rather than walking about checking valves and gauges.

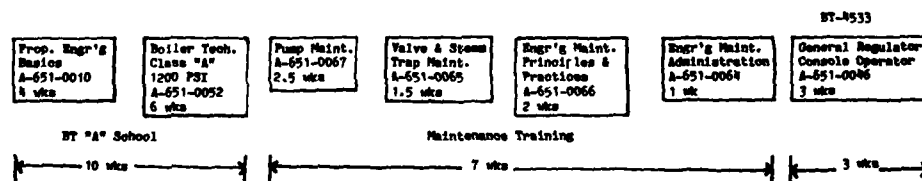
The U.S. Navy's commitment to gas turbine propulsion has meant a trade off involving fewer but more highly trained personnel.

TABLE 6

CG-26 PROPULSION
TRAINING PIPELINE



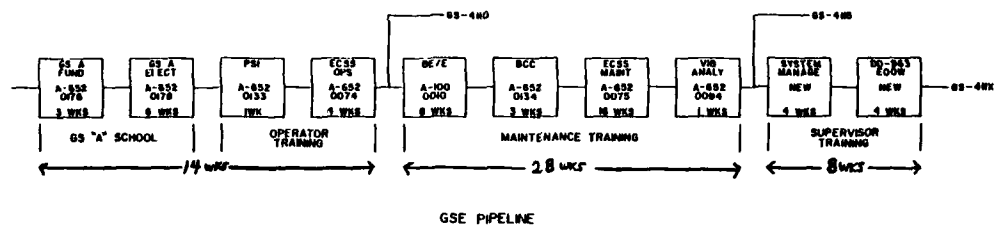
MACHINIST'S MATE (MM) PIPELINE



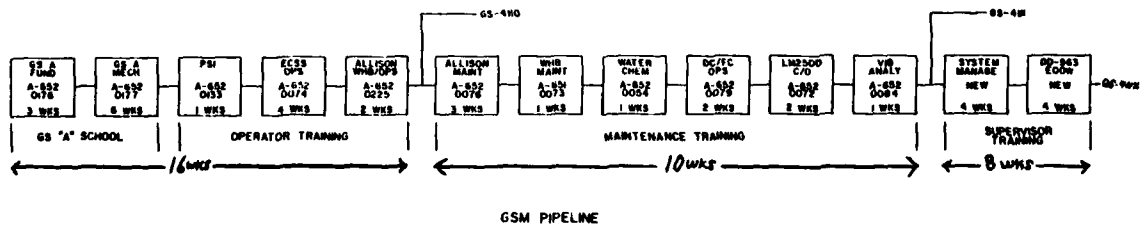
BOILER TECHNICIAN (BT) PIPELINE

TABLE 7

DD-963 PROPULSION
TRAINING PIPELINE



8-11



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PRACTICAL EXPERIENCE WITH MAINTAINABILITY AND RELIABILITY OF
ALPHAPROM, A MICROPROCESSOR-BASED MONITORING SYSTEM.

by P.G. Kempers,
Managing Director of
C.S.I. B.V. - Vlaardingen, Holland and
C.S.I. (Alphaprom) Ltd. - Reading, U.K.

INTRODUCTION

This paper deals with some practical points which I have found important during 20 years of experience with electronic systems on board of merchant navy ships. These points may not look very scientific, however, I am convinced that if they were given more attention, more electronic systems in ships' engine rooms would have been performing more reliable and they are still very much valid!

This paper also describes a micro-processor based monitoring system which is now used for the unmanned operation of nearly 100 engine rooms and has proven to be very reliable indeed, probably because many such seemingly insignificant points as mentioned above, were duly considered during the design stage.

DESIGNING AND SPECIFYING ELECTRONIC SYSTEMS

With the fast introduction of microcomputers on board of ships, a number of quite simple basic principles should not be forgotten. Unfortunately I have seen that in the hurry of developing ever more complex systems, such basic rules are not always obeyed, resulting in many, sometimes even fatal, errors, which are so obvious to the system-designer that he often neglects their existence.

Very often, problems arise where electronics start merging with other engineering disciplines, for example when applied to monitor and to control mechanical processes such as in a ship's engine room. The electronic engineer is reluctant to understand other engineering languages, which he thinks primitive anyway, whereas other engineers often are too modest to believe they will ever understand the "magic" of electronics!

Only people who speak both languages know that both points of view are wrong:

"Other" engineering is not by any means "primitive" and electronics is not at all "magic". It is just the relative novelty of electronics that makes it so difficult to come to a new mutual understanding.

Still many times basically sound electronic systems failed just because of this language difference and the initial confidence the marine engineer had in the system chosen.

Now that microprocessors are coming aboard and shipowners start to

put still more (sometimes even too much) confidence in electronics, I think considering the following points can help the marine engineer to judge the feasibility of a given electronic system for using it on board of one of his ships:

- If an electronic system gives the impression to a mechanical engineer that its mechanical construction is neat and obviously well designed, there is a fair chance that the (invisible) electronic circuitry is also well designed!
- If a printed circuit board shows one or two corrections obviously added at a later date, be extra careful!
If many P.C.B.'s in a system show such corrections (usually scratched-away conductors and/or added hand-soldered components) be suspicious and ask for the reason!!
- Marine engineers should specify their requirements more exactly and more clearly.
It often happens that a system, probably worth some \$ 200,000 is described in only one or two lines, resulting in quotations varying in values between \$ 50,000 and \$ 500,000! From the matching specs of such quotations, however, it is absolutely impossible to deduce what is really offered. Many times, after ordering, it is then discovered that the suppliers' interpretation of the final scope of delivery is by no means matching the original thoughts of the marine engineer who wrote this specs.
- Electronic specs, brochures and quotations shall be read like package-deal-travel brochures.
If something "can" be done it is never included and always costs more!
If you expect to get something which is obvious a forgotten detail, chance is that it is not available at all!
With the growing complexity, specifically of software, this problem becomes more serious every day!
- Marine engineers have very clear rules and ideas about their own craft. They know exactly when to accept and when not welds and soldered joints if it concerns a 2-inch pipe.
Why do not they ever dare to criticise the contents of an electronic cabinet with the same critics?

Accuracy

There is an unmistakable trend towards an increasing number of measuring points throughout the engineroom.
Engines and machinery can then be brought much nearer to their limits and calculation methods can be introduced for giving optimal information about their performance.

Non-instrument-engineers find themselves often in trouble when specifying the "accuracy" of a measuring point.
The engineer should be clearly aware of what is really meant by a given figure which should indicate the accuracy.

An accuracy of + 0.5% means plus or minus 0.5% of full-scale-value of the range in which a variable is measured. In other words: if you speak about a nominal value of "10" and an accuracy of 0.5%, you

might end up anywhere between "15" and "5" if you happen to have choosen "1000" as being the range!

Furthermore, accuracy without a reference to stability and repeatability does not give you the exact information. Also the accuracy of the sensor used influences the overall accuracy of the measuring loop.

It is also often neglected that the calibration accuracy of an ordinary thermocouple alone, for example may be 2%!

Practical experience shows that many engineers do not realize exactly that accuracy is only the resultant of a number of independant but well known factors.

Too much care sometimes results in requiring "0.1%", where "1%" would have been sufficient if properly specified. This breeds frustrated instrument engineers who start putting effort in the wrong places. Therefore it is very important that a marine engineer who specifies accuracy, knows very well what he is asking for.

When specifying "accuracy", two things should always be seriously considered for each individual measuring point:

- a) Not to ask for a better accuracy than what is really needed, and
- b) Not to accept lesser accuracy than what is really needed!!

USING MICROCOMPUTERS IN GENERAL

The last few years show a rapidly increasing use of microcomputers in industry and also on board of ships.

In our daily life we are in constant confrontation with all sorts of computer applications. We should not believe that it is always really so simple to fit a micro in everything.

What we see in our daily life is either the result of enormous capital investments from the users' side (mainframe systems) or from the manufacturers' side (consumer electronics).

Applying microcomputers to the marine industry, however, where often a "quantity" of one (1) is ordered, it is not so simple to get the same sort of reliable help from a computer-system as in the other two examples.

It is funny to see that many of the same shipowners, who were so reluctant to introduce the first pieces of electronics in the engineroom, back in the sixties, now are sometimes over-enthusiastic in imagining of computer applications on board of their ships! In fairness, however, it should be said that a similar development is seen in the shore-based industry!

Specifically the notion of "software" is sometimes beyond reality. For hardware-oriented people, as marine engineers always are, it is very easy to compare the solution of a given problem in software with a hardware-solution.

It can, however, not be repeated enough that software is, and will be for a while, only in its childhood and the potential of available hardware is much larger than the necessary software allows. This available hardware, however, is what is often only sold!

The ignorant, enthusiastic, new computer-user only discovers later

what problems he really bought: this hardware does not work without software!

The only way to arrive at a high reliability level with micro's on board of ships is to insist on field-proven software routines. Please refrain from requiring little individual refinements because such "little" extra's which seem so easy to add for the hardware-thinking engineer, but which are very dangerous. They could well upset the reliability of the original basic routine(s), which were so reliable in the beginning.

Although a lot of hardware comes available on the industrial microcomputer-market, only a very few items are "shipshape". Economy in manufacturing has resulted in single-board computers on very large printed circuits, which are unfit to withstand the vibrations, normal to the marine environment.

Also the use of the dynamic-RAM as memories in microcomputers for ships must be avoided. The basic electric principles of such memories (updating every microsecond or so) make reliable use on board of ships hardly possible. Static-RAM is far better to use.

Furthermore with the increasing data storage requirements, the using of floppy disks, common on the personal computer market, must be avoided by the marine user.

"Man-machine dialogue" is another topic to be approached with common sense.

Commercial statements, like: "the dialogue with the computer is by means of simple questions and answers, typed on a normal QWERTY-keyboard" are misleading.

The average operator is no typist, nor is he a computer expert, so the "dialogue" whatever that "buzzword" may be, must be very simple indeed and any complication in the operating routines must be avoided.

"Self-checking routines" are also to be watched with sound criticism. Although theoretically very well possible, usually the available budget to equip a ships' engineroom with a microcomputer-based monitoring system does not allow such features to a large extent. Again, the marine engineer should not be misled by computer-buzzwords, which are often "superlatives-by-definition".

The number of "bugs"(= failures), which make a system unusable for some time, or worse delete important data altogether, in land-based office computers is still substantial large. If you then realize that such systems run under nearly ideal circumstances, which use cast-iron-software routines, the marine engineer should take utmost care before "joining the bandwagon" of microcomputer users!

Please let the above, somewhat negative approach not at all keep you from using micros. If used in the right way the marine engineer of to-day may already have great help of them and the burden of the daily work in the unmanned engineroom can be lightened considerably by the micro if sufficient common sense is used.

EXPERIENCE WITH A MICROPROCESSOR SYSTEM IN ENGINE ROOMS.

This part describes "ALPHAPROM", an ALPHAnumerical PROcess Monitor, developed by C.S.I., firstly used in 1975 on the world's largest tanker, Shell's "BATTILUS" and now in use on board of nearly 100 ships.

This system distinguishes itself in two ways from other modern microprocessor-based systems by:

- a) Being specifically designed for use on board of ships, both, hard- and software-wise
- b) An integrated back-up system which ensures continuing of the monitoring process if the central processor should fail.

System Description

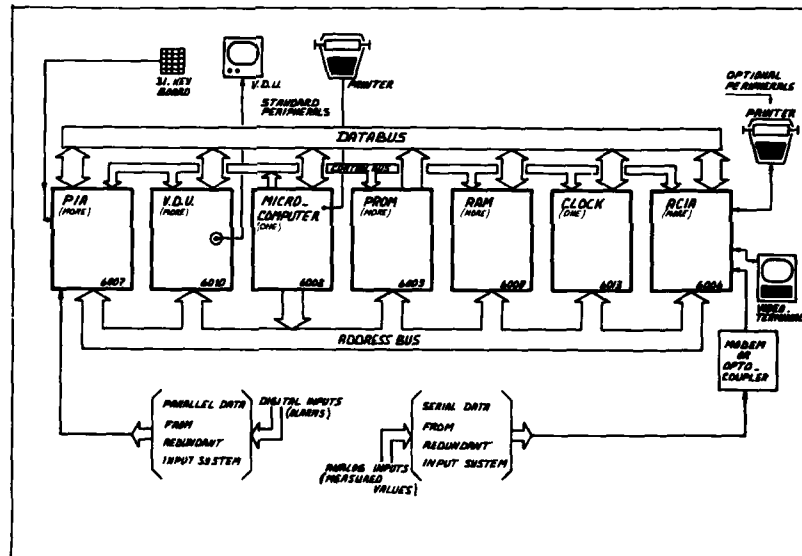


Figure 1

- Basic blockdiagram of the central processor unit.
- Each block represents one P.C. Board.
- Only the microprocessor- and realtime clock card are single,
- all others can be multiplied for larger systems.

Central Processor

The heart of the system is the microprocessor, based on Motorola's type 6800 microprocessor.

The basic diagram shows a conventional central processor as well as some memory and input/output interfacing cards. By adding more memory cards, the capacity of the system can be increased to a maximum of 1 Megabyte!

The system has V24/RS232 outputs for example to connecting a dataprinter, which can be programmed either as a log-printer or an alarm-printer, or as combination of both.

The system has a standardized video-output. The output specifications are: 625 lines, 1 V. peak-to-peak in 75 Ohms, which is the international I.E.C.-standard for video-monitors. Consequently, any standard T.V.-monitor can be used. This safeguards the availability of the V.D.U. (Video Display Unit), because now these units can be repaired or newly acquired really anywhere in the world.

The C.P.U. unit measures approx 19" x 8" x 14" and is fitted in the middle of a hinged-rack ("door") containing all electronics of the system.

Redundant - ("Back-up") - System

In general, when central processors are used, the inputcircuits are cut-down to a minimum, resulting in an attractive price, since the input scanners, controlled by the C.P.U., manage to successively putting each individual sensor to the one and only common measuring input.

In practice, however, and certainly for marine applications, a system, which is relying on only one single central processor is a dangerous system. Not much imagination is needed to see that only one little faulty component can make the whole unmanned engineroom system inoperative.

Even doubling the system with using 2 C.P.U.'s does not meet the theoretically acceptable 2-out-of-3 principle for reliability. Three C.P.U.'s however, are, to-day, still too expensive for the average shipbuilder's budget!

In order to come to an acceptable system-reliability, "ALPHAPROM" uses an inputsystem which in itself offers 100% redundancy.

This input system comprises complete individual input circuits for each (individual) input channel and is able to operate fully independently of the C.P.U. In this way the engineroom can be considered as being fit for U.M.S., even if the C.P.U. or any of its output devices, fails. The use of individual input circuits provides simple signal conditioning and efficient input filtering.

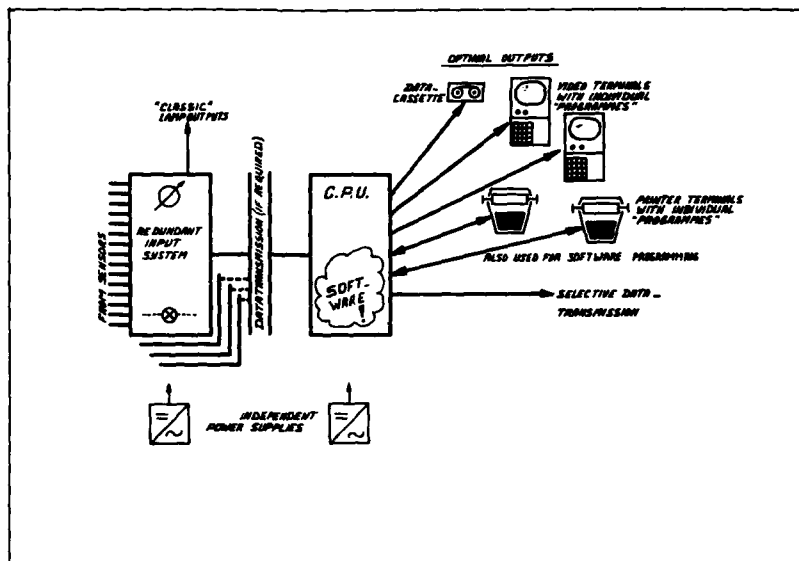


Figure 2
 - Basic principles of Alphaprom.
 - Redundant inputs work independtly of the C.P.U.
 - Datatransmission between input and C.P.U. is possible
 - if inputs are fitted remotely in local stations.

As each signal is individually amplified, the scanning can be done at high signal (voltage) level, avoiding many well-known problems due to switch-contact problems in the scanner if these were in the input (transducer) circuit.

HOW "ALPHAPROM" DEALS WITH VARIOUS INPUTS

a) On/off alarm signals

In this case, where all alarm information comes from on/off switches, the T.V. screen is the main source of alarm-information for the operator.

In case of no alarm, the screen is blank, only the first line indicates if the system is working correctly. If something within the system goes wrong, this first line shows nonsense or is not visible at all.

If an alarm arises, the second line shows the text of the alarmpoint as well as the point-number in a flashing mode. At the same time an acoustical alarm is engaged.

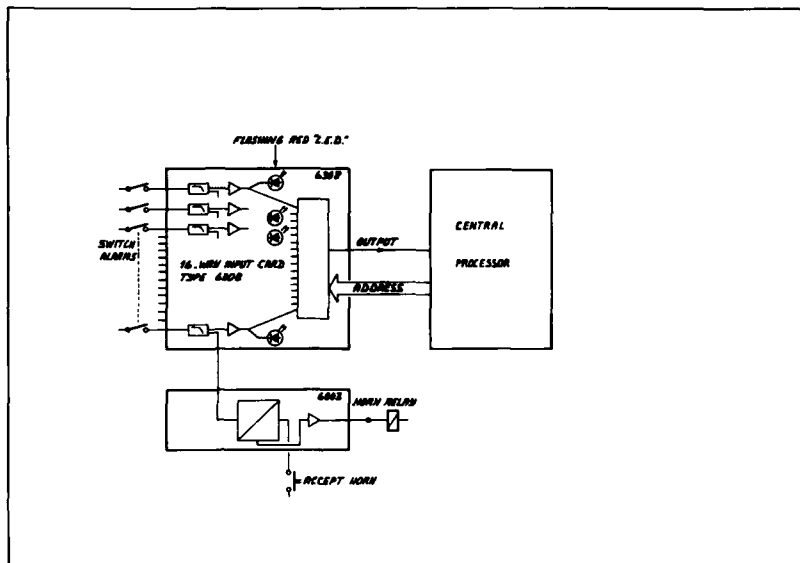


Figure 3
- Basic principle of the on/off inputs showing the
- redundant L.E.D.'s.

After acceptance, the flashing line becomes steady and the acoustical signal can be muted.

Each new alarm is annunciated in the same way until 21 lines on the screen are shown. This automatically ensures the chronological display of each new alarm entered. ("First-failure" indication).

The first alarm, the second, the third, and so on are shown in this way. If more than 21 alarms are present, the last line on the screen indicates that there are more alarms at the "next page".

By pressing the button: "Next page" it is possible to call for the next pages.

Also groups of measuring points can be called.

If the C.P.U. is not working (!) the redundant input system makes it possible to continue with operating the system. Each individual alarmchannel has its own LED (Light Emitting Diode), on the front panel of the main C.P.U. cabinet.

This LED has the same functions as a "normal" alarm point (off-flashing-steady-off), however, for the sake of simplicity, each LED is only equipped with a tagnumber, not with a complete text.

Sixteen (16) individual input circuits, each with their own filter and time delay, are built on 16-way input cards with 16 LED's . Sixteen 16-input cards (representing 256 alarmpoints), are mechanically fitted behind one window, tag-numbered 000...256. The redundant input system is powered separately by its own power-supply or the emergency battery and also serves the group-outputs to the cabins and the bridge as well as the initiating of the acoustical alarm, independently of the C.P.U.

b) Analogue Signals

In to-day's engineroom designs, more and more parameters are being measured by analogue sensors (thermocouples, resistance thermometers, pressure transducers, etc.).

In microprocessor-based systems, it is very attractive to use so-called "soft-setpoints", which can be set by the operators' keyboard and easily changed if the normal process parameters change. One disadvantage of this setting is that all setpoints have to be stored in memory, which is more or less volatile. In such cases it is a good idea to store the initial machinery trial data in EPROM and only the later changes in RAM. ALPHAPROM uses basically the "hard-setpoints" as set on each individual trip-amplifier. If required, they may be used as back-up for soft setpoints.

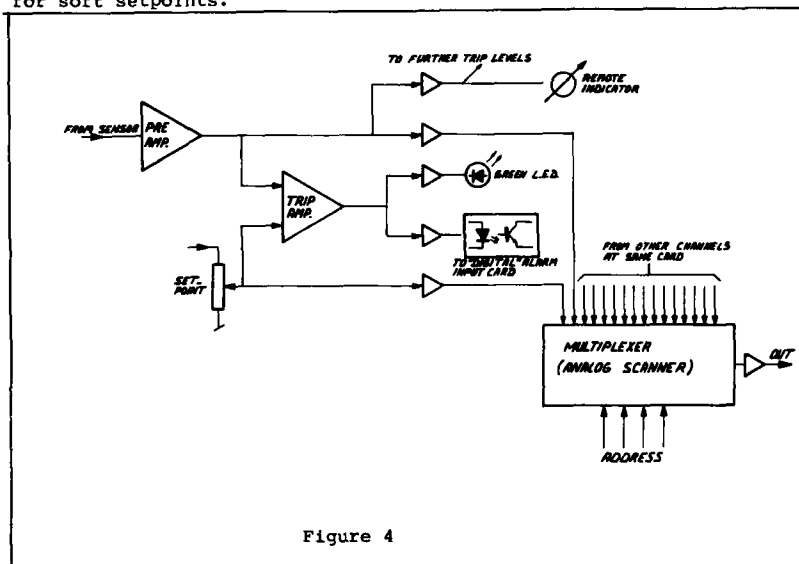


Figure 4

- Basic principle of the analogue inputs showing the
- various output facilities and the redundant hardware
- setpoints.

As all circuits work in parallel, the chance for a dangerous failure making many inputs inoperative, is very low. Built-in the central cabinet is a digital indicator which can be switched to each individual input amplifier to serve as an emergency indicator for the various pressures, temperatures, etc., as well as to check the (hardware) alarmsettings if the C.P.U. should be inoperative.

c) Distributed (remote) Input Stations and Telemetry

Two factors stimulate the rapid development of the decentralized system.

- a) The increasing costs of cabling between each individual sensor and the central monitoring system.
- b) The decreasing costs of microprocessors and the relative complex systems built around them.

A third factor, which has been used a number of times on board of Dutch ships, is the omitting of a central control room and bringing back of the monitoring information directly to the machinery concerned.

In such distributed systems it is, however, still more important to make sure that monitoring will not be made impossible by one little failure in one centrally used circuit.

The ALPHAPROM concept for decentralized systems is rather simple but effective:

- In each location a complete system including microprocessor, scanners and back-up system, including back-up power-supply
- is operating.

One system is designated as "management-computer" with which others communicate as "slave-computers".

Communication between the various locations is by straightforward modem-connections incorporating the necessary error-checking routines.

If communication is impossible, each local station can still work independently, whereas in the worst case, at any location, the back-up system is still fully available to keep its principal monitoring functions working.

Specifically with refrigerated container ships, which can carry up to over 1000 refrigerated containers, the use of a distributed system can be advantageous.

In such cases the measuring, setting and re-adjusting of each individual alarm can be a cumbersome job. The computer helps to do all this in a relatively easy way. "ALPHAPROM" provides for such applications individual pre-amplifiers for each individual measuring point, but as accurate hard-setting of each individual alarmlevel would be an impractical job, the setting of the alarms can be done "software"-wise in the C.P.U.

In case of a failure in the C.P.U., the separate input section still makes it possible to maintain the measuring of each individual cargo- or container-temperature.

STANDARD SOFTWARE ROUTINES

By using the programming facilities of the C.P.U., an increasing number of monitoring programmes are now available, such as:

Alarmsetting.

This can be done in various ways.

If all temperatures are different, all settings can be set individually.

If one setting is valid for all temperatures, which sometimes happens with reefer cargo temperatures, only one setting needs to be adjusted for all.

All possibilities between these two are also included.

Datalogging

By means of the alphanumeric printer a logsheet can be produced, which is formatted according to the ship's specific requirements. Date, time, ports of call, sort of cargo, etc., etc., are all data, which can be automatically printed together with the measured values at each single logsheet.

Exhaustgas temperature averaging.

For some time, exhaustgas-temperature averagers have been installed as separate units.

Standard routines in the software make it possible to incorporate these measurements in the overall monitoring system.

This simplifies the system design. Using the facilities of the computer also makes it possible to monitor each individual exhaustgastemperature with respect to the average much more accurately. (If the placing of the sensors and some other mechanical problems permit this anyway!).

Bearing temperature averaging.

Similar routines as for the exhaustgastemperatures can be used for medium speed engines to monitoring bearing temperatures.

Fuel consumption

If the engineroom monitoring system is computer-based, it can also be used for a number of calculations to optimise the fuel consumption. As a number of important parameters are already incorporated in the engineroom monitoring system, there will be no need for separate systems anymore.

Tank level measuring and -alarming

A complete software package has been designed for the use with tanklevel gauges on board of product- and chemicaltankers. Innage/ullage calculations, graphic bargraph displays of levels and

alarms are now available.

Cooling down.

This programme is designed for reefer-cargo monitoring. It avoids temperature alarms during the cooling-down of the cargo. As long as the temperature keeps falling, there is no alarm.

Bridge- and Cabin Alarms, Engineers' Safety System.

When the enginerooms started to become unmanned, it became important to inform the engineers in their quarters if something went wrong. At the same time, the bridge, which is still always manned, should receive some warning. The object of these warnings was (and is) to direct one or more engineers immediately to the engineroom, which from then on is "manned" again.

Of course the best solution for such remote warning system would be to transfer all information to all important places outside. Practical reasons, of course, made it necessary to reduce these remote signals to a minimum. So usually only a few group-alarm lamps were put forward. Unfortunately, however, there are as many principles and theories about this subject as there are Owners and Classification Societies in the world! Still their object has always been the same:

- Warn an engineer, order him to the engine room and
- supply him with sufficient pre-information to make
- him already thinking on his way down.

The possibility, given by data-transmission for example by sending information through a coaxial cable of a closed T.V. circuit, now makes it practically possible to fulfill the original dream of supplying all information to the engineer in his cabin.

In the ALPHAPROM system, again for safety reasons, the bridge- and cabin video monitors still are used as well as a "classic" group- and cabin alarm circuit, which is operated independently from the central processor unit.

SOME EXPERIENCE WITH RELIABILITY.

Many "ALPHAPROM" systems have been delivered to shipowners who have quite a well-organized administrative system for failures and service-calls. Furthermore C.S.I. keeps a complete logbook of all failures which ever called attention.

On the basis of these administration-systems it was possible to obtain a fair idea about the reliability of the monitoring systems in actual service.

In August '81 we have evaluated such figures of 38 systems in operation. The oldest of these installations was commissioned end 1975, the youngest in November 1980.

These 38 systems contain a total of 2570 printed circuit boards of various types, mainly inputcards.

The total number of operational hours was: 897170.

The total number of failures/repair on board and in our workshop was:

also includes all cases where a P.C.B. was interchanged on board the ships' staff and the defective card sent to our workshop results in an M.T.B.F. of 8231 hours or say 11.5 months for a complete system as an average.

Testing to find is furthermore that always during the first year (though each system is duly burned-in before commissioning) the number of "complaints" (sometimes serious failures, sometimes mistakes of the operator) is considerably higher than in the later years, where the operators get acquainted to the sort of system they are working with. The above figure is purely based on practice. Roughly speaking a shipowner may count on one failure once every year. Often the actual repair can be done on board by just interchanging a defective P.C.B. In most repairs the system is practically running uninterrupted because of the back-up system, so the actual availability or "up-time" is very high indeed.

CONCLUSIONS

The first part of this paper has shown you again that using common sense is always the most important basis to judging any technical product.

The second part shows you a system which, in 1981, is probably installed on more ships than any other system on the market. Its reliability figure may not be extremely high at first sight, but it is a reliable figure!

Furthermore, the sea herself, always having punished the overconfident, will finally also teach us how to steer correctly in the future with "microprocessors in the engine room!"

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